A ONE-DAY STATE-OF-THE-ART BRIEFING ON HIGH-SPEED GRINDING

March 13, 1969

Professor Opitz, Part I, morning session

Scientific Factors in Grinding

SCIENTIFIC FACTORS IN GRINDING

1 Introduction

Machinability research in the area of grinding has sought for a long time to understand or describe the relationships between the various parameters and to explain the physical phenomena. Systematic investigations for this purpose go in two directions:

1. Research on the kinematics of material removal and the physical parameters in grinding such as, for example, cutting forces, temperatures, and wear mechanisms.
2. Consideration for such grinding results as surface quality, tool life, and economics of grinding as well as all of the related questions associated with wheel dressing and cooling and lubrication.

Many of these relationships have not been well understood for the conventional grinding which has been in general use. Consequently, it became necessary to investigate these questions further as interest in the application of higher cutting speeds developed. From the numerous questions and the corresponding answers which have been obtained I have selected for this presentation only those which are especially significant for high-speed grinding.

2 Basic Laws of Metal Cutting

2.1 Study of Grinding Physics by Simulating the Process

In evaluating the grinding process one is concerned with the cutting forces and temperatures as they depend upon the properties of the work material and also with the surface quality on the workpiece and manifestations of wear on the wheel. In addition, knowledge of the grain distribution in the wheel and kinematic factors of the contact conditions are necessary. A method has been developed using a digital computer to simulate the grinding process wherein the influence of the contact conditions and grain distribution can be evaluated. This makes it possible to carry out a systematic investigation of the relationships between the several grinding parameters. Out of the numerous available publications on the removal mechanism in grinding one important point comes to the foreground. This concerns the difficulty in arriving at or developing undisputable basic rules through technical investigation and from the development of sufficiently accurate theory. The reason for this difficulty lies above all in the randomness and the three-dimensional character of the grain distribution of a grinding wheel as well as in the undefined geometry of the individual grains.

These conditions emphasize the need to determine exactly the path of each individual grain as it proceeds through the workpiece and to determine the spectrum of the results in relation to distribution of the grains and to the variable kinematic conditions. The first investigation in this direction has shown that it is possible to predict quite simply the way in which actual cutting forces and temperatures relate to chip thickness and contact length. Obviously, the cost of other methods available up until now have not permitted concurrent consideration of all of the most important influential parameters on the grinding process.

A digital computer offers a more advantageous way to approach the solution of this problem economically. Using this method experimental investigation and theoretical considerations of the grinding process have shown that the contact conditions between the tool and the workpiece have decisive significance for the evaluation of the grinding process. The contact conditions and ratios are determined basically by the following factors:

1. By the number, size, shape, and distribution of the abrasive grains as well as by their

physical and chemical properties.

2. By the kinematic conditions during grinding.

The application of the computer to the problem proceeds from the premise that a grinding wheel whose grain size and distribution is known will proceed through the workpiece in an ideal cut corresponding to the cutting conditions to be investigated. The distribution as well as the configuration of the grains can be determined quite simply with the aid of an apparatus or instrument equipped with a contact stylus. The profile of the entire perimeter of a grinding wheel is determined for a single plane, perpendicular to the wheel axis. For each condition of the wheel whether freshly dressed or in the worn condition, the profile record provides the radial position and the corresponding angular location for each grain. This information is digitized and becomes the input for a computer program.

Depending upon the selected cutting conditions as determined by the grinding wheel surface speed, the work speed and the depth of the layer to be ground, the program determines the path of each individual grain, the depth of its penetration and the actual length of

Fig. 1 contact. The upper half of Figure 1 shows an example of surface grinding for a grain distribution profile as determined for one revolution of the grinding wheel.

The line OO' corresponds to the upper edge of a workpiece with a geometrically ideal boundry. The material to be machined lies beneath this boundry line.

For the determination of the characteristic parameters it is necessary to determine that sequence of interference paths between the grains and the workpiece which would lead to chip formation. This task of calculation is carried out by the digital computer. The result is shown in the lower half of the figure. For the analysis or interpretation of these results it is useful and permissible to think of the area between the 00' line and the grain paths as longitudinal sections of the undeformed chips. A sufficiently large number of grains will yield a quantity of longitudinal chip cross-sections adequate to provide a representative average value which can be compared to similar values for various cutting conditions.

The computer program, among others, yields data on values of the chip thickness and the number of grains making contact at any given set of grinding conditions.

Fig. 2 Figure 2 shows the average maximum chip thickness in relationship to the depth of cut for four different grinding speed ratios. The directional trend of the curve indicates that chip thickness must exert a decisive influence on grinding forces. A comparison with research results of a practical type show, as will be discussed later, the same dependent tendency. With increasing depth of cut and corresponding increase in removal rate, the chip thickness as well as the cutting forces increase degressively. This indicates the effect of increasing the cutting speed ratio as well as the cutting speed itself whereby at constant removal rate the chip thickness and the cutting forces both decrease. The cutting force is distributed only over those grains which actually make contact for cutting. Such information can be obtained from a computer simulation of the grinding process.

Fig. 3 Figure 3 shows the number of grains making contact for one centimeter of the perimeter of the wheel as a function of speed ratio for various depths of cut. With increasing peripheral speed of the grinding wheel, the number of the grains taking part in the cutting actually decreases. This conclusion or result as a trend has been confirmed earlier through practical laboratory investigation.

The information included in Figure 1 also yields the surface profile of the workpiece. The profile is produced by the relative motions or paths of those abrasive grains which penetrate deepest into the workpiece.

Fig. 4 One can see in Figure 4 that increase either of the speed ratio or of the cutting speed exerts a favorable effect on the surface roughness. Increase of the speed reduces not only the number of abrasive grains making contact but also the chip thickness. Out of this results an improvement in the surface.

The results obtained by this method ought to show that it is possible to determine systematically the most influential parameters for any desired set of grinding conditions. Of course, the validity of the relationships is limited by the initial assumption that no deformation occurs either on the wheel or on the workpiece. However, it does provide a basis for interpreting variations and actual measurements of cutting forces temperatures and wheel wear.

Further research now being carried out will show to what degree computer solutions of these problems can be further improved.

2.2 Temperature Studies of the Grinding Zone

It has already been shown that the heat which necessarily accompanies any cutting operation is especially important in grinding.

The short contact time and the high contact frequencies of the abrasive grains creates considerable difficulties in determining the actual temperatures occurring in grinding. Despite the still inadequate theories on the creation and distribution of heat in grinding, the influence of cutting conditions on temperature in the grinding zone can be determined at least as a tendency out of the results which have been published up to this time. These include:

1. An increase of the material removal rate and the grinding wheel surface velocity will in every case lead to the development of increased heat.
2. Increase of the work speed diminishes heat development.

Since in high performance grinding one aims for the highest possible wheel surface speed and material removal rate, a corresponding temperature loading of the workpiece surface is to be expected. From this fact, it appears necessary to determine the influence of grinding wheel and workpiece surface velocities as well as material removal rates on the grinding temperature. A further objective is to find a suitable combination of workpiece and wheel speeds which can be held within boundries such that damage to the work surface can be eliminated.

Fig. 5 Figure 5 shows an arrangement for determining grinding temperatures through the application of a platinum-iron thermocouple. A platinum foil of 0.1 millimeters (0.004 inches) thickness is clamped and insulated between the two halves of a workpiece which has been split laterally. In order to obtain a simultaneous measurement of the average effect of numerous concurrent grain contacts, the width of the foil was extended to 8 millimeters. With this width a rapidly changing sequence of concurrent contact locations occur and each of them creates an electromotive force proportional to its temperature. This creates a parallel circuit of voltage sources in such a manner that the total electromotive force is a single voltage representative of all voltage sources. Thus, each grinding pass over the thermoelement gives an average temperature rising out of the many individual contacts.

The peak termperatures which arise in the case of rubbing contact between the workpiece and the worn area of the grains is conducted into the workpiece. However, in a very short time after the contact, the temperature reaches equilibrium with the surrounding areas. Through the rapidly occurring sequence of individual grain contacts an average temperature is established in the contact area between the wheel and the workpiece which can be assumed to be quasi-stationary during the short time of the grinding passes over a workpiece element. This average temperature is a decisive factor in the thermal-loading of the workpiece surface.

The temperatures determined in this study were based on the calibration of platinum and 1045 steel as the thermoelement. The comparison thermocouple used for the calibration consisted of a platinum-platinum rhodium couple.

Figure 6 shows the general relationship between grinding wheel surface speed v_s, removal rate Z', and the average temperature T_m, for grinding without a coolant. The surface speed of the workpiece was not varied. In this plot of test results one can see that an increase of the wheel surface speed creates higher temperature at all material removal rates. However, it should be noted that the removal rate exerts a far greater influence on the grinding heat then does the surface speed of the grinding wheel. For example, an increase in removal rate from $Z'=2$ to 10 cubic millimeters per millimeter per second because the temperature increase from 180^{o} Centigrade to 585^{o} Centigrade at a grinding wheel surface speed $v_s=20$ meters per second. By contrast, the corresponding temperature range for a wheel surface speed of $v_s=80$ meters per second, the temperature range is from 220^{o} Centigrade to 750^{o} Centigrade. This would indicate that at the removal rate of 10 cubic millimeters per millimeter per second and the cutting speed of 80 meters per second that the corresponding temperature in the cutting zone is already so high that if the heat were to be conducted into the work surface layer that it would lead to considerable thermal damage. A repetition of this test at the same conditions except for the additional application of a grinding oil showed that the temperature for a removal rate of $Z'=10$ cubic millimeters per millimeter per second was reduced to approximately one-half of the previous value. The results of this comparison are shown in the figure. Grinding with oil has a similar effect for increases in the surface speed of the grinding wheel. That is, it effectively minimizes the increase in temperature which would otherwise take place as a result of increasing the wheel surface speed. The increase of cutting speed from 20 to 80 meters per second, while grinding with oil, increases the temperature only about 20^{o} to 25^{o} Centigrade regardless of the removal rate.

Since oil has a relatively poor thermal conductivity, but good lubricating qualities, then it is permissible to assume that the minimizing of temperature can be attributed to reduction of friction.

The influence of work surface speed on heating of the grinding zone can be seen in Figure 7. This figure shows the temperatures determined for different grinding wheels used in dry grinding over a range of removal rates. Up to a work surface speed of 40 meters per minute the temperature is substantially reduced for all wheel surface speeds. A further increase of the work surface speed does not bring about any further significant advantage.

Fig. 7

The low temperature loading of the work surface at higher work surface speeds can be attributed to the following. At the high work surface speeds, the high temperature traveling heat source is present for such a short time that heat transfer is limited essentially to that work material in ahead of the grinding wheel, so that subsequent abrasive grains remove practically all of the heat which has been transfered into the workpiece in the chips themselves. Merely the friction heat created by rubbing between the worn areas of the abrasive grains and the workpiece succeeds in penetrating the finish ground surface.

This result, that is, the reduction of temperatures by increase of work surface speed at high grinding speeds can be attributed further to two additional facts. The first of these is that the frictional rubbing is also a traveling heat source so that an increase in work surface speed can be expected to result in a reduction of the amount of frictional heat transfered into a specific volume of the workpiece. The second factor arises out of the fact that the cutting forces are reduced at high cutting speed and this in turn leads to a reduction of the frictional heat as a result of lower normal forces acting upon the worn areas of the abrasive grains. At high work surface speeds, the influence of the cutting forces predominates while at lower speeds the influence of the rubbing velocity is greater. These two compensating influences balance each other out at a work surface speed of about 40 meters per minute.

It is evident from the aforementioned results that the speed ratio $q=v_s/v_w$, takes on a special significance for high performance grinding. A specific value of ratio q can be expected to provide an optimum set of conditions in the cutting zone. Figure 8 shows the important influence of the speed ratio q on grinding heat while grinding dry at constant removal rate. Large values of q, that is, high wheel surface speed in the presence of low work speeds leads to greater heat development. It will be noted that increasing the wheel surface speed at constant speed ratio brings about a substantial reduction in the average temperature, especially at the higher ratios. Since one of the objectives of high-speed grinding is a substantial increase in the removal rate, it becomes desirable to explore various ways to reduce grinding

Fig. 8

temperatures so as to permit further increases in the removal rate.

Fig. 9 Figure 9 shows the results from a series of tests in grinding 1045 steel at several different work speeds and a constant wheel speed of 80 meters per second while using oil as a coolant. The average temperature is plotted vs removal rate. It will be noted that at removal rates between 30 and 50 cubic millimeters per millimeter per second that the average temperatures for low work speeds already lie well within the Austenitizing region. By increasing the work speed from 20 to 80 meters per minute, the average temperatures in the contact zone are reduced nearly 75%. It will be noticed also that the highest temperature reached at a work surface speed of 80 meters per minute and a removal rate of 100 cubic millimeters per millimeter per second was only 780^{o} Centigrade.

Depending upon the speed ratio, the removal rate and cooling, grinding heat can lead to temperatures well within the Austenitizing area of steel. At unfavorable working conditions (high removal rate, low work surface speed) a transformation of the work microstructure is evident in the surface boundry. The strain of the affected zone and its microstructure were investigated on specimens of Ck 45 N and S 6-5-2 (HRc 63.5) for grinding at very low work surface speeds and without a coolant. Further work of this type led to the indication that thermal damage at the highest removal rates could be nearly completely eliminated either through increases of the work surface speed or through the application of grinding oil. The most unfavorable cutting conditions with dry grinding were obtained with a work surface speed v_w=5 meters per minute. At this relatively low removal rate of 10 cubic millimeters per millimeter per second, the rehardened layer of the normalized carbon steel extended to a depth of 275 microns (0.011 inches). Corresponding hardness measurements relative to the distance from

Fig. 10 the ground surface are shown in Figure 10. The causes for the increase of hardness to 510kp/mm^2 above the initial hardness is indicated further in the photomicrographs.

Even though the contacts of the individual abrasive grains at the high cutting speed of 80 meters per second created higher temperatures, the effect on the workpiece was less than at the lower wheel speed of 20 meters per second. This confirms the assumption that a larger fraction of the heat is carried away in the chips with increasing wheel speed. The figure shows further that the application of grinding oil reduces the thickness of the affected zone at the same grinding conditions from 275 microns to 30 microns (0.0012 inches). At the same time, the hardness increase from the matrix value of 265 to 300 kp/mm^2 was measured at which condition it was no longer possible to note any effect of cutting speed. A second possibility for minimizing

Fig. 11 the temperature influence in grinding is shown in Figure 11. Even in grinding without a coolant an increase of the work surface speed from 5 to 80 meters per minute alone not only the depth of the affected zone but also the magnitude of the rehardening reduces. Here again, the high grinding wheel surface speed exerts the lower influence.

The combination of both methods, that is, grinding with oil concurrently with increasing the work surface speeds brought the results expected from the corresponding temperature measurements. Microhardness tests could not detect any further affect on the work surface.

Studies of high-speed steel (S 6-5-2) led to the same results. Here, also, high wheel surface speeds led to smaller changes in the outer surface. The improvement of grinding results through high work surface speeds can be

Fig. 12 seen in Figure 12. The affected depth and the hardness differentials are substantially reduced.

The application of grinding oil was equally effective in reducing the temperature loading. Also, in the machining of the high-speed steel tool, the application of both methods (grinding oil and high work surface speed) produced no changes in the boundary zone that could be detected by microhardness testing.

The agreement of hardness measurements with microscopic examination of the affected depth can also be confirmed through metallographic examination.

Fig. 13 Figure 13 shows a hardness traverse compared to magnified photomicrographs for the ground surface of a 1045 steel. The machining conditions are given in the figure. At the right boundary of the photomicrograph one can see the pearlitic structure within ferrite areas of the normalized matrix material. As the ground surface of the workpiece is approached, the hardness increases because of the Austenite formation during grinding. At a depth of 200 microns the A_{c1} line must already have been overstepped since pearlite transformation is evident at the grain boundaries. Concurrently with the decomposition of the pearlite the carbon began to diffuse into the Austenite grains at the boundaries between the ferrite and pearlite grains. Diffusion took place significantly slower in the ferrite grains than in the pearlite. This is evident also in the specimen boundary where the Austenite has been formed from carbon poor ferrite grains in some areas and carbon rich pearlite grains in other regions.

From these results, one can draw certain conclusions for the practical application and use of higher cutting speeds and removal rates in grinding:

1. At conventional cutting speeds increasing the removal rate over that commonly used for rough grinding (Z'=3 cubic millimeters per millimeter per second) leads to a thermal overloading of the work surface.
2. An increase of the grinding wheel surface speed also leads to a temperature increase which, however, is substantially less than

the corresponding influence of higher removal rates.

3. In order to avoid structural changes in the work surface it is necessary to increase the wheel surface speed and the work surface speed together. The necessary proportional increase of both speed components signifies grinding with constant speed ratio q.

4. The speed ratio q for high removal rates and cutting speeds should not be greater than 60.

5. The highest removal rates possible without thermal damage of the workpiece can be obtained through the application of grinding oil and the aforementioned speed ratio q=60.

Influence of the Cutting Speed on Cutting Forces, Surface Finish and Wheel Wear

Theoretical considerations and the confirmation available from research results leads to recognition that the removal capacity of the grinding process can be increased through a suitable choice of cutting conditions. For this purpose, the wheel surface speed takes on special significance. The relationships between the wheel surface speed, the cutting forces, the work surface roughness, and the wheel wear can be seen in the next three figures and can be partially explained from kinematics and the mechanics of metal removal.

Fig. 14
Fig. 15
Fig. 16

If the wheel surface speed is increased at constant work speed, the number of contacts between abrasive grains and the workpiece at any instant is reduced. This depends upon the spacing of successive abrasive grains in the grinding path and also on the speed ratio q. This relationship can be determined by actual grinding tests.

A reduction of the number of grain contacts at higher wheel speeds indicates that the effective distance between successive grains is increased. It can be concluded from a kinematic analysis of the process in the grinding zone that higher surface speeds of the grinding wheel do indeed lead to greater spacing of the effective grains despite the higher motional velocities of the grains themselves. This is due to the fact that the average chip thickness and the average contact length of the individual grains become smaller. As a consequence, the cutting force necessarily becomes smaller. The smaller number of grains in the cutting zone arising out of the three-dimensional nature of their distribution do come more frequently, however, at high-speeds thus producing lower cutting forces and a better surface quality.

Since the cutting force can be defined as the sum of the individual forces of all of the grains participating at any instant, the loading of the individual grains also becomes smaller and less wear can be expected.

If the grinding wheel surface speed and the work surface speed are increased and in such a manner that the speed ratio q remains constant then the kinematic contact conditions between the grinding wheel and the workpiece change only to the extent that the removal process takes place faster in magnitude proportional to the increase in the respective surface speeds. This means that the removal rate will be increased proportionally even though the depth of cut remains constant. If these cutting conditions, that is, variable work speed and variable wheel speed are compared with each other at constant removal rate then it can also be established that the concurrent increase of both the wheel surface speed and work surface speed must lead to a reduction of cutting forces, surface roughness, and wheel wear. Thus, these results seem indisputable.

On the basis of these results, the application of higher cutting speed is possible in two ways:

1. The increase of cutting speeds at constant total removal rate in the same grinding time leads to better workpiece quality.
2. Any desired workpiece quality can be obtained faster with higher cutting speeds. The removal rate is substantially greater.

3.2 The Sonic Testing of Grinding Wheels

The optimum solution of the grinding task depends not alone upon suitable operating parameters but also in large measure upon a proper selection of the grinding wheel. It is equally important to both wheel manufacturer and wheel user as to what criteria and properties are important during cutting and how they can be evaluated. One of the most characteristic and most discussed parameters is the hardness of a grinding wheel. Since there is no adequate and unique definition for the concept, "hardness," the determination of this property for bonded abrasives requires some revision of procedures. The methods of hardness testing used up until now are characterized by the fact that they are only relative. Thus, grinding wheels tested by one method can be compared only qualatatively with those tested by another method.

Most of the hardness testing processes used up until now have been concerned with the strength of the bonds which hold the abrasive grains within the structure. Consequently, these methods use some form of force measurement as a means of determining that strength. A new process for evaluating properties analogous to hardness has been developed.

Professor Peters of the University of Louvain, Belgium, has undertaken an old idea in attempting to bring out the use of elastic modulus to characterize the grinding wheel. The basic idea proposes that the hardness of the grinding wheel corresponds to two physical properties:

1. The elastic modulus which primarily characterizes the abrasive bond.
2. The grain strength.

Both of these parameters describe or determine the operating characteristics of a grinding wheel. In order for the elastic modulus to be a usable criterion it must:

1. Have physical significance and be simple to measure in practice.
2. Have some relationship to other measuring methods and to describe the behavior of the wheel in cutting.
3. Be able to show some relationship to the composition of the wheel.

One of the principal reasons why the modulus of elasticity has not been used as a practical parameter in the past lies in the fact that no nondestructive measuring methods for it known. Developments in the area of electronics now make it possible to determine the modulus of elasticity easily and accurately through measurements of the resonant frequency of the wheel.

A simplified circuit diagram of this type of apparatus

ig. 17 is shown in Figure 17. The grinding wheel to be tested is excited into vibration by impact. A piezoelectric transducer transforms these vibrations into electric signals, amplified, filtered, and then shaped into rectangular pulses before arriving at a switching gate. Concurrently, the amplified signal is led to a detector and integrator which forms the envelope of the decaying vibration. The gate is opened only when the amplitude of the envelope drops below a threshold value and the disturbing harmonics have died

out. The gate permits eight pulses of a now rectangular measuring signal through. The transfer time for these pulses is measured with a quartz clock. The results appear as a digital indication and gives the time in microseconds for two periods. This makes it possible to determine the resonant frequency of the wheel. The resonant frequency for the mechanical vibration of a body is determined through a form factor and some physical constants. The form factor concerns the geometry and the size of the body. The physical constants consist of a modulus of elasticity, the density, and Poisson's ratio. The latter two quantities are known. Finally, the modulus of elasticity can be determined.
Fig. 18 The equipment for this type of test is shown in Figure 18.

Time does not permit discussing all aspects of the relationship between the modulus of elasticity and the hardness for grinding wheel in this presentation. Therefore, this discussion will be limited to a comparison of the results from this apparatus with those obtained with two other well-known test procedures—blast testing and scratch hardness testing.

If the values obtained from each process are alternately
Fig. 19 superimposed as in the following figures, a comparison can be made of the reliability of the individual test methods within typical boundaries. The comparison of the BLAST depth measurement (by Zeiss-Mackensen) with the bond forces determined by the scratch hardness apparatus shows a more sensitive resolution for the former process in the area of lower hardnesses, although a strongly attenuated differentiating

the interdependent relationships between the tool and the cutting conditions in a systematic manner. Results from practical studies have confirmed the relationships already found. The results of applying these findings to actual grinding can be reconfirmed through hardness and metallographic studies of ground workpieces. In one final consideration a new method for the determination of grinding wheel hardness was presented. This process has the evaluating capability of other already known hardness test procedures. However, it has in addition to this advantage the further advantage of providing simple and rapidly reproducible measure values.

This presentation has been limited deliberately to reporting on the fundamentals obtained from research studies. Building on these results and the knowledge obtained from them, we can now proceed to a discussion of the applications of high-speed grinding from the viewpoint of those factors which are important in practice. This will be done in my second persentation this afternoon.

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Professor Opits, Part II, afternoon session

Current and Potential Applications of High-Speed Grinding

CURRENT AND POTENTIAL APPLICIATIONS OF HIGH-SPEED GRINDING

1 Introduction

For approximately 40 years it has been known that increasing the cutting speed in grinding made it possible to increase the removal rate, that is, the time based rate of material removal except that a higher wheel wear occurs. In spite of the undisputed advantage, the use of this knowledge in the grinding process was limited to such operations as cutoff and rough grinding where there is no concern for size and shape accuracy or surface quality. For these operations, that is, cutoff or rough grinding conventional practice uses plastic bonded and often fabric reinforced grinding wheels. This fact, and above all, the meager knowledge of the material removal process has delayed up until now the application of higher cutting speeds to precision grinding where predominately ceramic bonded grinding wheels are used.

Both research and practice indicate correspondingly that it is possible through increase of the grinding wheel surface speed to bring about a reduction of the cutting forces, and improvement of the surface finish as well as a significant reduction of the wheel wear.

From the viewpoint of the mechanics of cutting, these improvements are attainable for all grinding operations ranging from the shorter grinding time for more conventional operations through the elimination of prior machining onto workpieces out of the more difficult to machine materials. Thus, grinding with high cutting speeds advances the level of the process to the point where it is unique and will hereafter be designated as high-speed grinding.

2. Prerequisites for Application of the Process

The application of high-speed grinding focuses attention on some of the more important measures necessary for its successful introduction.

2.1 Reduction of Temperatures

In spite of the still inadequate theories concerning the creation and distribution of grinding heat available research results regarding the influence of cutting conditions on temperature in the grinding zone have established the tendancy that at otherwise equal conditions an increase in cutting speed leads to greater heat development in every case. The successful introduction of high-speed grinding depends, therefore, upon the effectiveness of measures taken to either remove the heat more rapidly out of the grinding zone or to minimize the heat developed. Thermal damage in the workpiece surface that can be detected through cracks and microhardness tests as well as with optical and electron microscope studies can be substantially eliminated through suitable choice of cutting conditions and the application of cooling and lubricant.

2.1.1 Speed ratio q

One possibility for reduction of the heat developed in grinding lies in increasing the work speed. The smaller temperature loading at higher work speed is attributed to the effectively shorter times that the individual heat sources are in contact with the work surface. The enlarged quantities of heat from the shear plane and the points of separation can no longer penetrate into the deeper zones since subsequent grains remove a larger fraction of the heat in the chips.

Substantially, only the frictional heat created by rubbing of the worn areas of the grains on the work surface has an opportunity to be transferred into the work-
Fig. 1 piece. Figure 1 shows the important influence of the speed ratio q on the average temperature measured in the contact zone. The values are valid for a constant removal rate and for dry grinding. These conditions were selected to emphasize the influence of speed ratios. Large values of q, that is, high wheel surface speed over low work speeds lead to greater heat development. As an example for q=192 (an unfavorable ratio) shows the creation of undesirable transformation of the microstructure in the boundary layer which

is accompanied in most cases by burn marks and grinding cracks. Thermal damage can be avoided even in dry grinding if a favorable speed ratio is held as the photomicrograph in the left half of the figure shows. The wheel surface speed of 80 meters per second was held constant while the work surface speed was increased from 5 meters per minute to 80 meters per minute so that a desirably low speed ratio of q=60 was approached. In this way, the temperature was caused to drop to approximately 185° Centigrade and an undesirable influence of the surface area is no longer distinguishable.

The speed ratio of q=60 appears to be about optimum since a further increase of the work speed brings no significant advantage from a technical standpoint. On the other hand, however, a more powerful workpiece spindle drive would be required for further increases.

2.1.2 Cooling and Lubrication

There is one further possibility for the reduction of the heat developed and for more rapid removal of the heat. This is through the application of a cutting fluid. From a technological viewpoint it is necessary for a good cutting fluid to have the following properties:

1. Good wetting ability.
2. Good heat transfer capacity.
3. High lubricity.

4. High specific heat.
5. High heat of vaporization.

It is necessary also to place the following requirements on the cutting fluid,

- that it create no damaging influence on the operating personnel,
- that it produce no deterioration in either the work material, machine parts, or the grinding wheel,
- that corrosion protection of the machine is assured,
- that the cutting fluid have a long life, and
- that protection against bacteriological growths is provided for.

WATER-EMULSION and above all pure grinding oil lend themselves well to applications in high-speed grinding. Compared to grinding oils water-emulsions have higher heat transfer capability and higher heat of evaporation. However, the higher wetability and lubricating capacity of the oils led to lower temperatures in the cutting zone and for this reason permits higher removal rates as the superposition of the attainable removal rates from emulsions and oils indicates

Fig. 2 in Figure 2.

The criterian used to determine the maximum attainable removal rate designated in the figure as boundary removal rate was the breaking down of the bond bridges in the cutting zone. The beginning of this breakdown can be determined precisely through cutting force measurements. In spite of the obvious advantages of the oils over the emulsions, the oils do have some disadvantage. This is evident in increased cost which limits the application of oil. The chemical industry should concern itself with the development of cutting fluids which possess both the cooling ability of oil-water emulsions as well as the high lubricating capacity of oil.

Some results in this direction have already been obtained

Fig. 3 as indicated in Figure 3. Proof of the suitability of various cutting fluids can be carried out in a special thread grinding operation. The criterian for the suitability of the cutting fluid is the wear on the outer profile radius after grinding for a specified distance. This relationship, that is the wear, is shown for several cutting fluids in the figure. It is evident that the performance capability of oil-water emulsions can be improved through changing the concentration of the oil components, thus, approaching the performance of pure grinding oil.

2.1.3 Wheel Dressing

Grinding at high wheel surface speeds makes it necessary to give brief consideration to the dressing of grinding wheels.

High-speed grinding is not limited to any specific dressing method. Which method should be used depends much more upon the nature of the manufacturing operation. The basis for decision here could be the fact that it is possible in high-speed grinding not only to reduce the grinding time but also to reduce the non-grinding times especially that for wheel dressing. With single point dressing tools such as single point diamonds, the increase in the wheel surface speed leads to a proportional decrease in the dressing time since the feedrate per revolution of the wheel is held substantially constant.

A more effective method of dressing is to be found in the application of diamond rolls with which complicated profiles can be produced in the shortest times and with greater accuracy. Despite the greater frequency of wheel dressing required with diamond rolls compared to single point diamonds, the substantially smaller infeed required by the rolls leads to lower total wheel wear. It should be emphasized at this point, that the fractional cost contributed by wheel dressing by whatever method will be greatly reduced if the work loading and wheel dressing operation can take place at the same time.

Because of the relatively high tool cost, the use of diamond profile rolls makes sense only in repetitive mass production. However, greater profile accuracy and better surface finish can be obtained than is now possible with individual diamonds.

3 Requirements of Machine and Machine Elements

In order to take full advantage of the use of high-speed grinding for improvement of the workpiece quality and increase of the removal rate it is necessary to make the grinding machine as well as its force transmitting elements compatible with the higher rotational speeds and higher cutting forces.

3.1 Improving the Spindle Bearings

High cutting speeds require high spindle rotation speeds. For a grinding wheel whose outer diameter, for example, is 400 millimeters (10 inches) and with which a surface speed of 60 meters per second (12,000 fpm) is to be used a spindle speed of about 2,900 rpm is required. Since the frictional power in a plain bearing increases with the square of the rubbing velocity, the higher rotational speed of the spindle leads to substantially increased heat development in the bearing. In extreme cases, an after cooling of the spindle oil is required to avoid overheating of the spindle bearings.

3.2 Higher Dynamic and Static Stiffness

If the performance capacity of high-speed grinding is to be fully achieved, that is, large quantities of workpiece material removed in the shortest possible time, cutting forces occur in greater magnitude than in conventional grinding practice. This condition must be considered quantatively in connection with both the machine foundation and the wheel and workpiece drives.

3.3 Higher Work Speed

If the workpiece drive involves the use of belts, then the changing of the corresponding sheaves or pulleys must consider the full-range of workpiece diameter so as to obtain the desired speed ratios.

For example, workpieces with a diameter of 3 millimeters (approximately 1/8th inch) to be ground with the wheel surface speed of 60 meters per second and a speed ratio of q=60, that is, with a 60 meter per minute work surface speed, then the workpiece must be rotated at 2,400 rpm.

3.4 Required Drive Power

The necessary spindle drive power can be determined from the tangential cutting force component. The product of this component and the work surface speed gives a work spindle power while the product of this same component and the wheel surface speed yields the spindle power.

'ig. 4 Figure 4 gives an example of the change in power requirements for high-speed grinding at a substantial increase in removal rate. An increase of the wheel surface speed from 30 to 90 meters per second (3 x conventional speed) requires a 70% increase in spindle drive power that at the same time yields 7 times the removal rate that was possible at the lower speed. This example indicates the direction which the projected development of new grinding machines must go if the greatest possible use of this process is to be made.

3.5 Cutting Fluid Equipment

It has already been indicated that removal of heat from the grinding zone presents a special problem. The cause for inadequate lubrication and cooling in the grinding zone is the moving air film caused by the high peripheral velocity of the grinding wheel. Through decoupling and the creation of vortices in this layer or by pumping the fluid under high pressure this disadvantage can be avoided. The greatest effectiveness can be obtained by a combination of both methods. High pressures and the large quantities of flow for this purpose require complete coverage of the working space. Delay of the operator by the spraying fluid can be avoided through partial cover when conventional oil-water emulsions are used. However, on the contrary complete covering must be provided when oil is to be used as the fluid. The smoke developed while grinding with oil can be removed by an exhaust system, or through a spark suppressing umbrella of oil from a surrounding secondary orifice or by grinding in an oil bath. Depending upon the viscosity, the filtering of the oil can be carried out either in centrifugal filters or separators. Whether or not, after cooling of the oil is required depends upon the available quantity.

3.6 Balancing of the Wheel Spindle Combination During Rotation

One of the most important conditions imposed by grinding at high surface speeds is the necessity for competent compensation for the unbalance of the grinding wheel including the flange, spindle, and drive elements. In order to keep the cost down for this necessary operation it is desirable to apply balancing apparatus which can compensate for unbalance in the shortest possible time while the spindle is rotating.

3.7 Increase in Machine Cost

Necessarily those measures designated as necessary for the use of high wheel speeds lead to higher costs of the machine itself. The expenditure for rebuilding as well as for new designs of machines for high-speed grinding depends upon the requirements imposed by the process. If one aims only for the quality improvement of the ground product then the cost is limited to improvement of the spindle bearing. On the contrary, if a higher removal rate in the shortest possible time is desired then it becomes compulsory to make basic changes throughout the design of the grinding machine. The result is a new type of grinding machine which provides for optimum adaptation which includes the omission of all nonfunctional machine elements.

4 Description of a High-Speed Surface Grinder

The aforementioned machine building concepts have been included in the construction of a new type of surface grinder developed in my institute.

'ig. 5 Figure 5 shows this machine with which grinding wheel surface speeds up to 24,000 fpm and a maximum spindle power of 35 kilowatts (47.5 horsepower) can be attained. The spindle bearings were so designed that the maximum possible stiffness could be obtained. The spindle bearings consist of a combination of antifriction bearings and hydrostatic bearings. The bearing arrangement is so designed that the cutting force is taken up only by the hydrostatic bearing while the antifriction bearings remain substantially unloaded and have been included only for the purpose of locating the spindle within the quill. Radial cutting forces cannot

'ig. 6 create a bending load on the drive spindle. Figure 6 shows that the bearing consists of four pairs of pockets which are supplied through capillary orifices. The stiffness of the forward spindle bearing was measured and found to be 75kp per micron (4.13 pounds per microinch or over two tons per thousandth).

Similarly a high stiffness was desired in the machine housing. Calculations were directed at obtaining both high static and high dynamic stiffness. Both the machine bed and column were made-up as a welded construction whereby the arrangement of the ribbing was based upon model structures. The static stiffness of the column was determined for the most unfavorable force contact position with the wheel head in the highest position. This resulted in a measured stiffness of 25kp per micron (1.38 pounds per microinch or 1,380 pounds per thousandth).

ig. 7 Figure 7 shows the overall stiffness between the table and the grinding wheel in relationship to the overhang of the quill. The superposition of similar stiffness measurements of a conventional surface grinder of heavy construction and constant overhang of the spindle carrier indicates that with equal forces hydrostatic bearings lead to lower deformation.

It is necessary also for a high-speed surface grinder to provide for a sufficiently high work speed. This means, on the one hand, that the table must be accelerated and decelerated very rapidly at the extreme position in order to provide constant speed for the largest possible longitudinal table travel. Therefore, the friction forces in the ways must also be kept as small as possible. Here also advantage was taken of the hydrostatic bearings.

ig. 8 Figure 8 shows the cross-section of the hydrostatically supported table.

The oil supply is made from a central groove in the middle of the table by way of capillaries and membrane orifices. The table is hydraulically driven. Table speeds up to 80 meters per minute (264 fpm) are attainable. In order to minimize undesired vibrations of the table due to the low table weight and small damping effect of the hydrostatic ways it was necessary to throttle the return flow of the oil.

Since the quill is movable and forms a common unit with the spindle drive motor, value must be placed on the lowest possible weight of the drive motor. For this purpose, therefore, a hydraulic apparatus was installed wherein the actual drive motor is separated from the supply pump. Additional gain resulted from the substantially smaller space requirement compared to the corresponding three

Fig. 9 phase induction motor of the same power. Figure 9 shows that in every performance area the hydraulic motor with regard to weight per unit of power as well as the corresponding volume is superior to the electric motor. The maximum rotational speed of the axial piston hydraulic motor is 2,500 rpm at rated power. Through positioning of the pump hanger the speed is steplessly variable from zero to 2,500 rpm. At a speed of 100 rpm which is necessary for steel crush dressing rolls this drive provides a sufficiently constant speed.

The biggest problem with high-speed grinding as obtained with high surface speeds of the grinding wheel is the heat created in the grinding zone which must be solved through adequate cutting fluid equipment. The simple cutting fluid nozzle which applies the fluid without pressure to the grinding area cannot be applied in high-speed grinding.

The air cushion which rotates with the grinding wheel prevents the fluid from arriving in the grinding zone. A high-speed grinding machine must, therefore, be equipped to supply the fluid to the grinding area under high pressure and in sufficient quantity. In this particular surface grinder the fluid is supplied at 150 liters per minute (40 gallons per minute) and with a pressure of 15kp per square centimeter (213 psi).

The unpublished requirements concerning well balanced grinding wheels for all grinding operations apply in greater measure for high-speed grinding.

The customary method of balancing with adjustable weights in the wheel flange cannot be used economically in high-speed grinding. The balancing must be carried out while the machine is running. The Cincinnati system cannot be used in this case because of the special shapes of the wheel flanges. A balancing apparatus must be used which can be flange mounted on the spindle nose. In this case, weights are adjusted in two axes during the running of the spindle until a minimum imbalance has been reached. The high bearing stiffness will prove to be an advantage only in so far as the imbalance has been reduced to a value which is no longer measurable. Unless this is done it will have an effect on the grinding results.

5 Safety Precautions

The German safety specifications for ceramic bonded grinding wheels currently permit a surface speed of 60 meters per second (12,000 fpm). However, in order to achieve the economic advantages of higher cutting speeds it will be necessary to broaden these specifications since grinding wheels depending upon their hardness, structure and geometric form show breaking speeds of the order of 100 to 150 meters per second (20,000 to 30,000 fpm). It therefore appears appropriate as well as expedient to increase the protective equipment on the machine itself so that an eventual break of a wheel is fully protected against. This idea has already been agreed to by the DSA. Consequently in the future not only the grinding wheels, but also the safety equipment of the machine itself will be licensed for high cutting speeds.

6 Performance Capacity and Limits

Assuming that the prerequisites for the successful introduction of high-speed grinding have been fulfilled it is now appropriate to discuss the performance capacity of this new process and to indicate the boundaries or limits for its application.

It goes without saying that not all of the manufacturing problems which fall into the area of conventional grinding can be better solved by increasing the cutting speed. On the other hand, it should be emphasized that the special advantages of high-speed grinding now open up completely new areas for application of the grinding process. This fact will make it necessary in the future to analyze every machining situation not only from a technological but also from an economic viewpoint. Typical examples of these considerations have been selected from industrial manufacturing and shall be discussed in the following.

The advantage of high-speed grinding which can be achieved with the least expenditure or investment consists of the quality improvement of the ground workpiece where the criteria for the evaluation are the shape and size accuracy as well as the surface quality. High cutting forces lead to deformation of the entire system, grinding wheel suspension—grinding wheel—workpiece—workpiece support, and contribute to deterioration of the quality of the workpiece.

As mentioned at the outset, increasing the cutting speed can reduce the cutting forces when the removal rate remains unchanged. This advantage, among others, was used in the

Fig. 10 grinding of a valve seat as shown in Figure 10.

By grinding at a wheel surface speed of 60 meters per second compared to conventional speed, the lower cutting forces made it possible to hold tolerances on the overhanging valve within narrower limits. In this way, the seat was held within a roundness error of 1.5 microns (60 microinches). The attainable location accuracy relative to the shank of the valve was held to a runout of less than 1.5 microns. Similarly, the arithmetic average roughness, which is important to the function of the valve, was held to 0.3 microns.

Cutting forces have an especially unfavorable effect on the shape accuracy of hollow cylindrical workpieces.

'ig. 11 Figure11 shows a thin walled plunger piston with a wall thickness of 2 millimeters. At a grinding wheel surface speed of 34 meters per second, the cutting forces were so high that the part could not be held to the required size and roundness tolerances either by through feed or plunge feed centerless grinding.

By increasing the surface speed to 60 meters per second, the cutting forces are dropped low enough so that the piston can meet the roundness specifications. As an additional gain the grinding time was also reduced about 85%. This latter advantage will be discussed separately later on.

An alternative arising out of the reduction of specific cutting forces consists of the possibility for increasing the width of the areas being ground so that two or more surfaces can be machined concurrently. This advantage can be used for the worm shaft shown in

ig. 12 Figure 12. The right half of this relatively slender shaft was ground earlier in two operations at the surface speed of 30 meters per second. In the first operation that portion with the longitudinal keyway was ground while the second operation took care of the bearing surface.

Now, at a cutting speed of 60 meters per second and the same rate of material removal per unit of wheel width a profile plunge grind of over 100 millimeters width including the shoulder is possible. As a result of the lower specific cutting forces the out-of-roundness of all these surfaces lie within the tolerance. Roundness errors arise through the increased cutting pressure in passing over the keyway with the markedly reduced grinding widths used up until this time.

The second objective which the application of high-speed grinding offers is the reduction of grinding time. That means that the necessary workpiece quality can be reached faster with higher cutting speed. The mutual dependent relationships between the wheel surface speed, the removal rate, and the cutting forces as well as the surface roughness makes it possible to predict quantitatively the attainable timesaving.
Fig. 13 Typical relationships are shown in Figure 13. The cutting forces in grinding are the principal determinants of the shape and size accuracy of the workpiece so that if one considers that a specific cutting force of 2kp per millimeter (110 pounds per inch) is permissible then a removal rate of approximately 3 cubic millimeters per millimeter per second can be obtained at a wheel surface speed of 20 meters per second. On the other hand, if the wheel surface speed is increased to 90 meters per second, the limiting cutting force value of 2kp per millimeter will not be reached until the removal rate has been increased to 33 cubic millimeters per millimeter per second. Thus, increasing the cutting

speed to $4\frac{1}{2}$ times the original value leads to an increase to 11 times the initial removal rate where the normal force component must be limited. Since the removal rate is defined as removal per unit of time this corresponds to a grinding time reduction of 90%.

ig. 14 Figure 14 shows a similar relationship of the surface roughness to the removal rate and the wheel surface speed. One can see, for example, that a roughness of 1.0 micron obtained with a cutting speed of 20 meters per second occurs at a removal rate of 1 cubic millimeter per millimeter per second, while the same surface roughness for a 90 meter per second wheel speed results in a removal rate of 12 cubic millimeters per millimeter per second. Here, also, increasing the speed to $4\frac{1}{2}$ times makes it possible to reduce the grinding time more than 90% for the same surface roughness specification.

Basically, the objective of reducing the grinding time is available for every grinding operation. However, there are some specific difficulties encountered in external plunge centerless grinding which will be explained through an actual
ig. 15 example as shown in Figure 15. The difficulties arise out of the fact that the workpiece is not put into rotary motion before it comes in contact with the grinding wheel. In the instance of initial contact and the beginning of grinding there is a temporary out-of-roundness of two to three microns which at a wheel surface speed of 30 meters per second and 0.1 millimeters available to be ground off, can be overcome

before the final size is reached.

At a surface speed of 60 meters per second, however, the tangential cutting force is considerably smaller so that the wheel penetrates material approximately twice as far before the workpiece reaches the prescribed rotational speed. Consequently, the roundness error cannot be overcome at 60 meters per second so that the required accuracy cannot be achieved. Of course, this error could be overcome by providing more material to be ground off, however, this in turn would increase the grinding time correspondingly. Consequently, one must conclude that higher grinding wheel surface speeds should not be used for plunge centerless grinding of parts with high rotational inertia which would prevent them from coming up to the desired speed quickly.

The greatest advantage of high-speed grinding will be derived only when not only the high cutting speed is used but also the highest removal rate. Which values in the region of boundary removal rates that can be obtained at
g. 16 extreme conditions today are shown in Figure 16. In this case, a slot is ground in the head of a bolt or stub shaft. This operation is comparable to the so-called plunge grinding.

The grinding wheel surface speed at 120 meters per second lies near the upper boundary that currently is determined by both the machine and the properties of the grinding wheel. With the workpiece velocity of 6 meters per minute the grinding wheel required only about 0.2 seconds to remove all of the material out of the slot. The surface finish was free of burn marks not only at the base of the slot but also on the side surfaces. The parallelism of the flanks lies within the required tolerance. The removal rate of 1,500 cubic millimeters per millimeter per second (60 cubic inches per minute) is considerably greater (500 to 750 times) than the two to three cubic millimeters per millimeter per second obtained by conventional grinding.

It is apparent in which direction grinding technology is developing as a consequence of using the possibilities which have been sighted. In all cases where previous turning and milling operations are necessarily followed by grinding the advantage of the high removal rate combined with the accuracy that is attainable through grinding it may be possible to eliminate previous or intermediate turning or milling operations. In a sequence of manufacturing operations it seemed appropriate for example to proceed directly to grinding of cold formed parts or to use grinding where large numbers of parts are to be made from bar stock.
ig. 17 A characteristic example of this is shown in Figure 17 for the manufacture of injector nozzle bodies.

A suitable grinding machine for this purpose already exists in the form of an automatic bar machine in which two injector bodies are ground from the bar material in a single cycle. The nature of the cycle can be noted in the figure. In this example, high-speed grinding performs the function of both rough and finish machining since the initial removal takes place at high feedrate while the finish machining of the surface is carried out at a low feedrate. Each diameter and the shoulder are finished concurrently along with the chamfer and finally the grinding wheel cuts the finished injector body off. The cycle time is less than a minute and this fact combined with the accuracy attained indicates where the advantage lies.

The saving of turning or milling operations is not alone among these advantages. At particular conditions, grinding at high surface speeds is indeed superior to either turning or milling in regards to the removal rate as for example the grinding of a slot in hardened blank. In drill manufacture this knowledge has been used with
ig. 18 success for a long time. An example is shown in Figure 18 where a cutting speed of 120 meters per second produces a removal rate in grinding the drill flute which is an order of magnitude greater than for milling. This example indicates a further possibility. That is, using a grinding operation to produce finished parts directly in one operation from hardened blanks. Such a manufacturing sequence can become appreciably more efficient and more economical.

It is significant, finally, that the advantage of high-speed grinding extend also to the machining of those materials which are difficult to cut. Included here among others is the machining of hard iron rolls. A further example, is the grinding of hard coated poppet valves as shown in

Fig. 19 Figure 19. In spite of cantilever support of the valve a relatively large removal rate can be attained since the increased cutting speed in combination with the application of oil as a cutting fluid leads to a reduction of the cutting forces.

The grinding infeed amounts to 1.5 to 2 millimeters. The profile wheel first contacts the valve seat and then finish grinds the poppet diameter and the fillet intersecting the valve shaft.

Up to this point the work examples introduced have been selected to give an indication of the performance capabilities of high-speed grinding itself.

As already explained, however, the aim is toward the highest possible total removal rates. High removal rate and corresponding short grinding times do not always signify the most efficient way to manufacture a product. Information about the most favorable manufacturing method from a cost viewpoint must be limited here to considerations of economy. Without going into detail, this matter will be discussed in connection with the machining of an automotive steering knuckle. One criterion that enters into economic considerations in a very large measure is grinding wheel wear which in turn depends upon the wheel surface velocity and the removal rate. The grinding wheel can be used only down to a specific diameter. Consequently, when they are used on machines where either because of cost or space a steplessly variable speed is not provided then decrease in diameter and the correspondingly lower speed results in higher cutting forces whose increase must be limited. This in turn, makes it necessary to reduce removal rate. Thus, in the case of constant speed wheel spindles, the wheel cost greatly outweighs the cost of diamond crushing rolls which practically can be neglected. Rough grinding without prior turning operations naturally brings yet other problems into consideration. Flat shoulders representing a fairly large range diameter and in the case of the steering knuckle mostly interrupted are difficult to machine and have a negative effect on the life of a grinding wheel.

A second way to approach the steering knuckle problem involves grinding after a prior turning operation with which the contour is produced in rough steps so that the grinding infeed can be substantially increased over what it would be in grinding from the solid. The diameter steps are so laid out that the diameters need not be decreased by more than about 7 millimeters during grinding.

Instead of the previous finish grinding the operation becomes rough and finish grinding with both being performed at 60 meters per second. Since now there are only rough machining operations on the lathe and no grooves which must be plunge cut, the tool cost will be reduced in this case.

Consequently, the optimum machining conditions for the steering knuckle lie in the middle between the original processing consisting of rough and finish turning and associated rough and finish grinding on the one hand and the machining completely by grinding on the other.

7 Summary

With these examples, the prerequisities for the introduction of high-speed grinding as well as the performance capacity and the boundaries or limits of this process have been illustrated.

An essential conclusion from this is that the increase of the cutting speed makes it possible to significantly increase the performance capability of the grinding process in relation to the quality of the ground workpieces and in regard to the removal rate. This possibility opens up completely new opportunities for grinding technology. It will be a question of time as to when the present boundaries and limits established by the strength of grinding wheels, the effectiveness of the coolant, as well as the design of the grinding machine and its elements can be extended so that the greatest possible use of this new process can be attained in practice. However, in every case of potential machining applications the prerequisities and operating conditions should be accurately analyzed so that the introduction of high-speed grinding is economically justifiable.