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RECENT ADVANCES IN GRINDING

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INTRODUCTION

Two decades ago grinding was almost totally applied as a finishing process working at very low removal rates and correspondingly low productivity. At those times grinding was used mainly because other methods could not provide the required geometrical accuracy or could not cut hardened materials at all. In the recent years, however, the situation has changed substantially. Still used as the dominant finishing process, grinding has been developed such that increased removal rates at constant or increased accuracy became possible. Also high-efficiency grinding of difficult-to-machine materials like stainless steels, tool and high speed steels, titanium and nickel-cobalt-base alloys, is performed today at a larger scale.

This development has been anticipated by a representative group of manufacturing experts assessing the undeveloped potential of the grinding process a few years ago /1/. Figure 1 reflects the group opinion for some selected statements. The majority, for example, expected new abrasive materials and exact analytical methods to describe the grinding process to become effective between 1980 and 1990. The substitution of other manufacturing processes by grinding is expected to increase steadily; grinding itself, however, is expected to be never substituted by other manufacturing processes completely. Other statements were evaluated in a more conservative way: About 30% of the questioned experts think that grinding wheel speeds applied in production will never be increased to 300 m/s (60000 sfpm), and 25% believe that grinding will never cover 50% of all finishing operations.









STATEMENTS	PROBABILITY					EXTREMES	
	1970	1980	1990	2000	Never	never %	irrelevant %
Introduction of new abrasive materials, other than Al_2O_3 , SiC, ZrO_2 and diamond						0	4.1
Grinding will replace 25% of all machining operations.						13.7	0
Grinding wheels with defined grain geometry and uniform structure						8.2	4.1
Availability of exact analytical methods to describe the grinding process						13.7	0
Grinding will perform 50% of all finish operations.						24.6	1.4
Availability of composite type grinding wheels employing whiskers						0	0
Grinding wheel speeds used in production will be increased to 300m/s.						28.8	0
Grinding will be substituted totally by other machining operations.						67	

Figure 1: Delphi-Type Forecast of the Future of Grinding /1/

Comparing these statements with today's state of art we realize, that the actual developments are pretty well following the predicted path: New analytical methods are in use to describe and control the grinding processes, and cubic boron nitride is applied as a new synthetic abrasive material for grinding hardened steels and superalloys. Actually the development of grinding technology as achieved in the last ten years can be split into three sections:

- Analysis of technological fundamentals,
- Development of processes and machines,
- Developments of tools and auxiliaries.

In the following chapter a detailed list of the most relevant advances in these three areas is presented together with pertinent references. Subsequently selected topics are discussed in detail.

RECENT DEVELOPMENTS IN GRINDING

The most important prerequisite for a substantial progress in grinding is the better understanding of the process fundamentals. Consequently, in the recent years major efforts have been

directed towards the analytical investigation of the kinematic and mechanical principles of material removal in grinding. At the same time processes have been studied and further developed aiming to achieve higher productivity and increased quality by means of modified or improved machines, tools and auxiliaries. The following list gives a representative overview on the most important advances in the different areas of grinding technology:

1. Analysis of Technological Fundamentals

1.1 Functional Description of Kinematic Relations /3/

- Number and distribution of static cutting edges,
- Number and distribution of dynamic cutting edges,
- Average chip cross section and chip thickness,

1.2 Functional Description of Grinding Forces /3,4,5,6,7,8/

- Mechanic principles of chip formation,
- Total normal and tangential grinding forces,
- Mean force per individual cutting edge,
- Time-dependant character of grinding force,

1.3 Functional Description of Wheel Wear /2,3,9,10,11,13/

- Mechanic principles of wear at bonded abrasives,
- Difference between radius and edge wear on grinding wheels,
- Cost-optimal grinding conditions,

1.4 Functional Description of Grinding Temperatures /4,12,14,15/

- Basic influence of friction and chip formation,
- State of temperature in contact zone,
- Temperature field in work surface layer,
- Wheel surface temperature,

1.5 Functional Description of Work Surface Roughness /11,16,17/

- Basic roughness due to wheel topography,
- Kinematic roughness due to process conditions,
- Mechanical roughness due to plastic deformations,

2. Development of Processes and Machines

2.1 Advances in Grinding Machine Design /18,19,20,21,22,23,52/

- Application of axiomatic principles for machine tool design,
- Increased static and dynamic stiffness,
- Increased working power,
- Infinitely variable drives for wheel and work,
- Electro-mechanical high-precision drives for tables and slides,
- Improved systems for cooling fluids, application and handling,
- Improved safety measures,
- Improved systems for precision feeding and stopping,

- Improved systems for automatic wheel balancing,
- Integrated and improved dressing devices,
- Temperature control of machine and coolant,

2.2 Advances in Control Techniques /23,24,25,26,27,28,29,30/

- Automatic compensation of wheel wear and dressing losses,
- Automatic control of dressing cycle,
- Control of thermally and mechanically induced distortions,
- Minimizing of idle operation times,
- Optimizing of step grinding,
- Programmable control techniques,
- CNC-control of surface and external plunge grinding,
- Adaptive control techniques,
- Sensor development for force, wear and roughness,
- Establishment of grinding data banks,

2.3 Process Modifications /49,50,51,52,53,54,57,58,59/

- High speed grinding,
- Creep feed grinding,
- High speed creep feed grinding,
- Speed stroke surface grinding,
- Form grinding of worms and gears,
- High speed belt grinding,
- High efficiency thread grinding,
- High efficiency roller grinding,

3. Development of Tools and Auxiliaries

3.1 New Abrasive Materials /31,32,33,34,35,36,38/

- Clustered diamond powder,
- Cubic boron nitride (CBN),
- Zirconia alumina,

3.2 New Bonding Systems /34,37,39,40,41/

- Vitrified bonding for CBN-wheels,
- Brittle bronze bonding for crushable CBN and diamond wheels,
- Resin bonding systems with metal filler and solid lubricants for CBN and diamond wheels,

3.3 New or Improved Dressing Systems /21,42, 43,44,45,46/

- High precision diamond rollers,
- Roll-2-dress device,
- Crush dressing of metal-bonded CBN and diamond wheels,
- Dia-dress system for vitrified CBN wheels,
- Single-point dressing for conventional wheels with polycrystalline sintered diamond tool marked by positive rake angle,

3.4 New or Improved Auxiliaries /22,24,47,48/

- New clamping system for high speed grinding wheels,
- Grindo-Sonic device for wheel grading,
- Hydraulic wheel balancing system,

The analytical study and description of the grinding process is the key to a better understanding and control. Controversal findings as experienced in using super-abrasives and applying high speed and creep feed techniques can well be resolved in the light of better understood fundamentals. For advanced control techniques, on the other hand, a reliable modeling system, in form of mathematical functions as well as pertinent sensors, is the most important prerequisites for the crucial identification of the controlled processes. Based on these fundamentals and on emperical investigations, the realisation of significantly improved productivity and work piece quality in grinding can be achieved by improved machines, tools and auxiliaries. The great variety of recent advances proves, that grinding indeed offers a considerable contribution to increased manufacturing productivity.

SELECTED EXAMPLES OF PRACTICAL ADVANCES IN GRINDING

1. Analytical Description of Grinding Forces

The force generated during grinding is one of the most relevant process criteria because it determines energy consumption, wheel wear and thermal load in the work surface. Using the symbols v_s = wheel speed, v_w = work speed, a = depth of cut, $D = d_w \cdot d_s / (d_w + d_s)$ = equivalent wheel diameter, d_s = wheel diameter, d_w = work diameter, C_1 = cutting edge density at wheel periphery, $l_k = (a \cdot D)^{1/2}$ = contact length between wheel and work piece, l = variable of contact length, $\bar{Q}(l)$ = average chip cross section as a function of the contact lenth variable, $N(l)$ = number of active cutting edges as a function of the contact lenth variable, the following definition for the grinding force per unit of grinding width b_s can be determined from the basic law of chip formation forces /6/:

$$F'_n = k \int_0^{l_k} [Q(l)]^n \cdot N(l) dl \quad (1)$$

Inserting the functional equations for $\bar{Q}(l)$ and $N(l)$ as derived and described in /2,6/, this function yields to a simply structured grinding force model:

$$F'_n = \frac{K}{\epsilon} [C_1]^Y \left[\frac{v_w}{v_s} \right]^{2\epsilon-1} [a]^\epsilon [D]^{1-\epsilon} \quad (2)$$

$$\text{where: } \xi = \frac{1}{2} [(1+n) + \alpha(1-n)]; \quad 0.5 < \xi < 1.0 \quad (3)$$

$$\gamma = \beta(1-n) \quad ; \quad 0 < \gamma < 1.0$$

The exponential coefficient n depends on the material ground and represents the degressive nature of increasing cutting forces versus chip cross section. Its numerical value is always positive and smaller than 1.0. The coefficients α and β represent the nature of cutting edge distribution in the wheel periphery and depend on wheel structure, dressing process and state of wear. The proportionality factor K is dependent on the cutting edge geometry, the cooling fluid properties, and the work material properties. Its dimension kp/mm^2 (pounds per square inch) is identical to the specific energy dimension.

Equation (2,3) can be derived on a much simpler way, too. Obviously the total grinding force is composed of two different components: friction and chip formation forces. Frictional forces can be related to the actual contact length $l_k = (a \cdot D)^{1/2}$ and the cutting edge density C_1 . Formational forces, on the other hand, are directly related to the total sum of all instantaneous chip cross section in the contact zone $Q_{\text{mom}} = a \cdot v_w / v_s$. Superimposing these two terms such that the influence of both varies reciprocally between 0 and 1 by employing an exponential coefficient $0 < \xi < 1$:

$$F'_{\text{in}} = \underbrace{C_1^\gamma [K \sqrt{a \cdot D}]^\beta}_{\text{frictional term}} \cdot \underbrace{[K \cdot (a \cdot v_w / v_s)]^{1-\beta}}_{\text{formational term}} \quad (4)$$

leads to exactly the same equation for the grinding force as (2,3) by applying the substitution $\beta = 2 - 2\xi$. Thus, the nature of grinding forces as a superimposed system of frictional and formational forces, which both depend on mechanical, kinematic and geometric process parameters, has been proven.

For practical applications it is important to notice, that materials with high ξ -values near 1.0 have a very good grindability with respect to thermal conditions. They have a ductile-hard character and don't generate much friction in micro-cutting; they form regular chips, do not tend to load the wheel surface with work material, and show a clear tendency for constant work temperatures when the wheel speed is increased. Materials with low ξ -values near 0.5 have a rigid-hard or ductile-soft nature, they are marked by an very high component of frictional forces in chip formation, form a debris-type of chip, and show a significant tendency for increased work temperatures when the wheel speed is increased. These material-dependent characteristics of the micro-chip formation process in grinding are being studied extensively

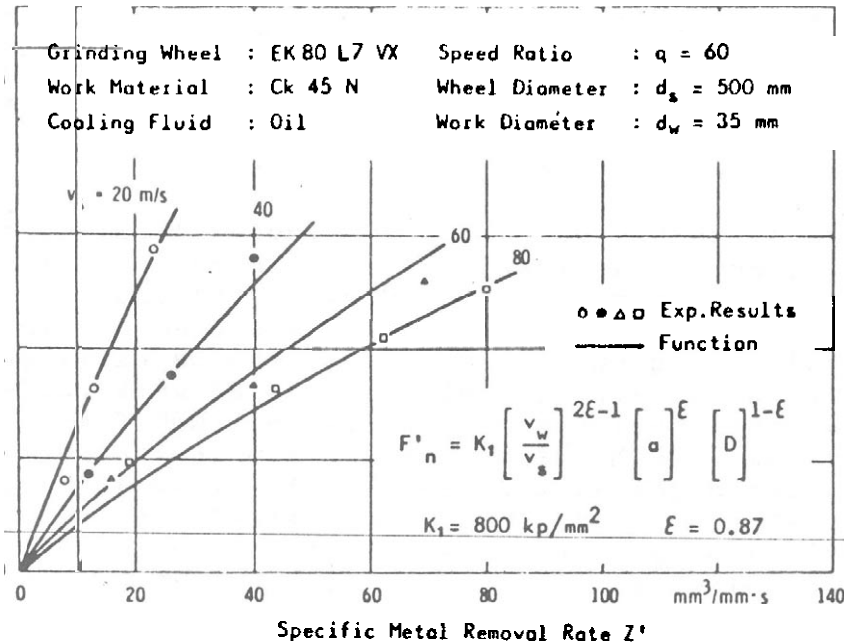


Figure 2:
Grinding Force
Model Applied to
External Plunge
Grinding Results

in Europe, and grinding data banks are being established at the same time, thus, making use of the analytical and practical results of university-industry cooperation /24,5/. As an example for these activities Figure 2 shows the application of the described force model to practical results obtained in external plunge grinding of a medium carbon steel (equivalent to AISI 1045) being ground with a conventional Al_2O_3 wheel using oil as coolant.

II. Application of Higher Wheel Speeds and Temperatures Aspects

The energy consumed in grinding per unit of grinding width b_g can be understood as the product of the tangential grinding force F'_t and the wheel speed v_s . Assuming as a first approximation, that the amount of energy flowing into the work surface is a constant proportion of the total energy, whereas the rest becomes effective in the chips, the grinding wheel and the cooling fluid, then the maximum temperature T_{max} in the work surface can be regarded as proportional to the total energy E per unit of grinding width:

$$T_{max} \approx E = F'_t \cdot v_s \quad (5)$$

This means that the work surface temperature increases proportionally with the wheel speed v_s , provided that the tangential grinding Force F'_t per unit of grinding width remains fairly con-

stant versus v_s . This is exactly true when the coefficient ϵ in (2,3) is near 0.5, i.e. with brittle-hard or ductile-soft materials. However, when ϵ has a value near to 1.0, as valid for ductile-hard materials with good grindability, then the tangential force decreases at the same rate the wheel speed goes up, and consequently the work surface temperature must remain constant and independent from the wheel speed v_s in this case.

This interrelation has clearly been proven by practical investigations /56/, and it is well known by general practical experience, too. Figure 3 shows the temperature behaviour of eight different materials, obtained by practical measurements in surface grinding. Basically two groups of materials can be distinguished: The first one does on an average not show higher work surface temperatures when the wheel speed is increased 100% from 30 m/s (6000 sfpm) to 60 m/s (12000 sfpm). This group consists of the following materials: High-alloyed steel X 210 Cr 12 (Chromium steel with Cr = 12%, C = 2.1%), high speed steel S 6-5-2 (equivalent to M1 steel), medium carbon steel Ck 45 N (equivalent to AISI 1045), and cobalt-base superalloy ATS 115 with Co = 52%, Cr = 20%, W = 15%, Ni = 11%, and all of them do qualify for the application of increased wheel speeds. The other group shows a significant increase of work surface temperature when the wheel speed is doubled: Low carbon steel C 15 (equivalent to AISI 1015), cast iron with globular graphite GGG 70, nickel-base superalloy RGT 12 with Ni = 58%, Cr = 20%, Co = 18%, Ti = 2%, Fe = 2%, and

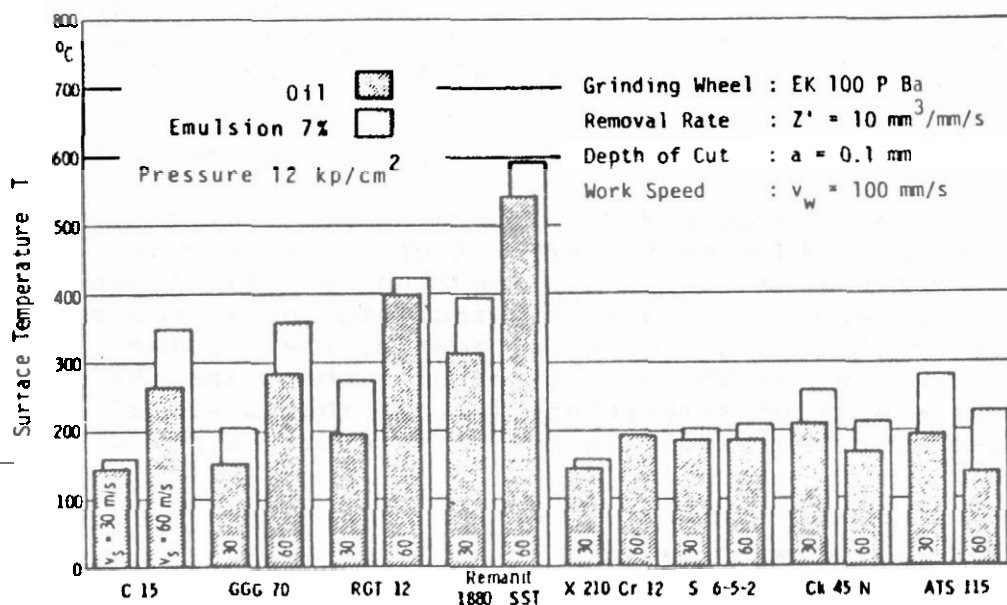


Figure 3: Surface Temperatures at Increased Wheel Speeds /56/

austenitic stainless steel Remanit 1880 SST with Cr = 17%, Ni = 12%, Mo = Ti = 2%. These materials are not suited for grinding with higher wheel speeds, because they are marked by a high frictional force component indicated by a low ξ -value. Consequently, this second group of materials shows a more significant drop of temperature when oil instead of emulsion is used as coolant, thus, reducing the considerable frictional energy by better lubrication.

If these simple force-related fundamentals would have been known ten years earlier, a lot of frustrating attempts could have been avoided, aiming to increase productivity in grinding at all means by applying higher wheel speed with all materials. In the bearing industry where group-1 type of materials with outstanding grindability are used by tradition, high speed grinding is regarded as a strong and successful method to increase productivity. In the turbine blade industry materials of group-2 type are used mainly; here the implementation of high speed grinding was bound to fail.

Some examples for successful application of increased wheel speeds in production grinding are:

- a) External cylindrical grinding of standard ball bearing rings /20/. The race of the internal ring is ground with 120 m/s (60000 sfpm) on a FAMIR RTF-C2 high speed grinding automat, using a vitrified sandwich-type Al_2O_3 wheel and an emulsion as coolant. The part time was reduced from 39 to 2.1 seconds, a 2000% productivity gain resulted in the production of 1370 races per hour, and production cost could be reduced 75%.
- b) High speed - creep feed grinding of twist drill flutes made from S 6-5-2 high speed steel, which is according to Figure 3 well suited for higher grinding wheel speeds /51/. Both flutes are ground out of the annealed full material in one pass on a specially designed machine, using resin bond Al_2O_3 wheels at 120 m/s (60000 sfpm) and oil as coolant. Achieved metal removal rates of $115 \text{ mm}^3/\text{mm/s}$ are 15 times higher than in milling the flutes, and surface integrity standard is clearly increased.
- c) Crank shaft grinding with wheel speeds increased up to 80 m/s (40000 sfpm) and increased metal removal rates /57/. Work material: chilled iron, hardness: $HR_C = 50$.

III. Creep Feed Grinding

One of the most promising recent developments in precision manufacturing is the creep feed grinding method. In comparison with the conventional pendulum surface grinding technique this

process provides a great potential to encrease productivity and accuracy at the same time /19/. This is especially true if deep and/or profiled slots have to be machined in difficult to machine work materials. Furthermore, creep feed technology offers an improved stability of the grinding wheel profile, and it shows a considerable reduction of thermal effects in the work surface.

Generally the creep feed surface grinding process is marked by a specific mode of operation. In contrast to the conventional pendulum technique, the depth of cut is increased 100 to 10000 times and the work speed is decreased in the same proportion. Thus, it is possible to grind slots with a depth of 1.0 to 30.0 mm (0.04 to 1.2") and more in one pass, using work speeds from 0.75 to 0.025 m/min (30 to 1 ipm), and reducing machining times 40 to 80%. In addition, profile stability is increased considerably.

An important prerequisite for making full usage of the economic and technological advantages of this high-efficiency / high-precision technology is the application of specially developed and constructed machine tools, grinding wheels, dressing methods, and controlling techniques. Such a system should provide the following features:

- High static and dynamic stability of machine tool,
- High accuracy, stick-slip free slides with favourable damping characteristics,
- Considerably increased spindle power,
- Infinitely variable spindle revolution number,
- High-balanced and directly connected motor-spindle system,
- Pre-tensioned, high performance, high accuracy spindle bearings,
- Non-hydraulic, single unit table drive covering the whole work speed area from creep feed to pendulum region,
- High pressure cooling and cleening system,
- Interated dressing devices,
- Pertinent grinding wheels,
- Up-dated process know-how.

Conventional surface grinders cannot at all provide these advanced features, and even modified conventional machines cannot meet with most of these necessary requirements. This is the reason why many attempts to change over to creep feed technology failed. The first creep feed prototype for surface grinding was developed in 1958, and in 1963 the first couple of production creep feed grinders were applied in practice /58/. Since then this technology has steadily been improved, and application has grown significantly. Today several grinding machine manufacturers offer creep feed machines, even for external plunge grinding, and as a consequence this technology can now be regarded as a well established and competitive manufacturing alternative.

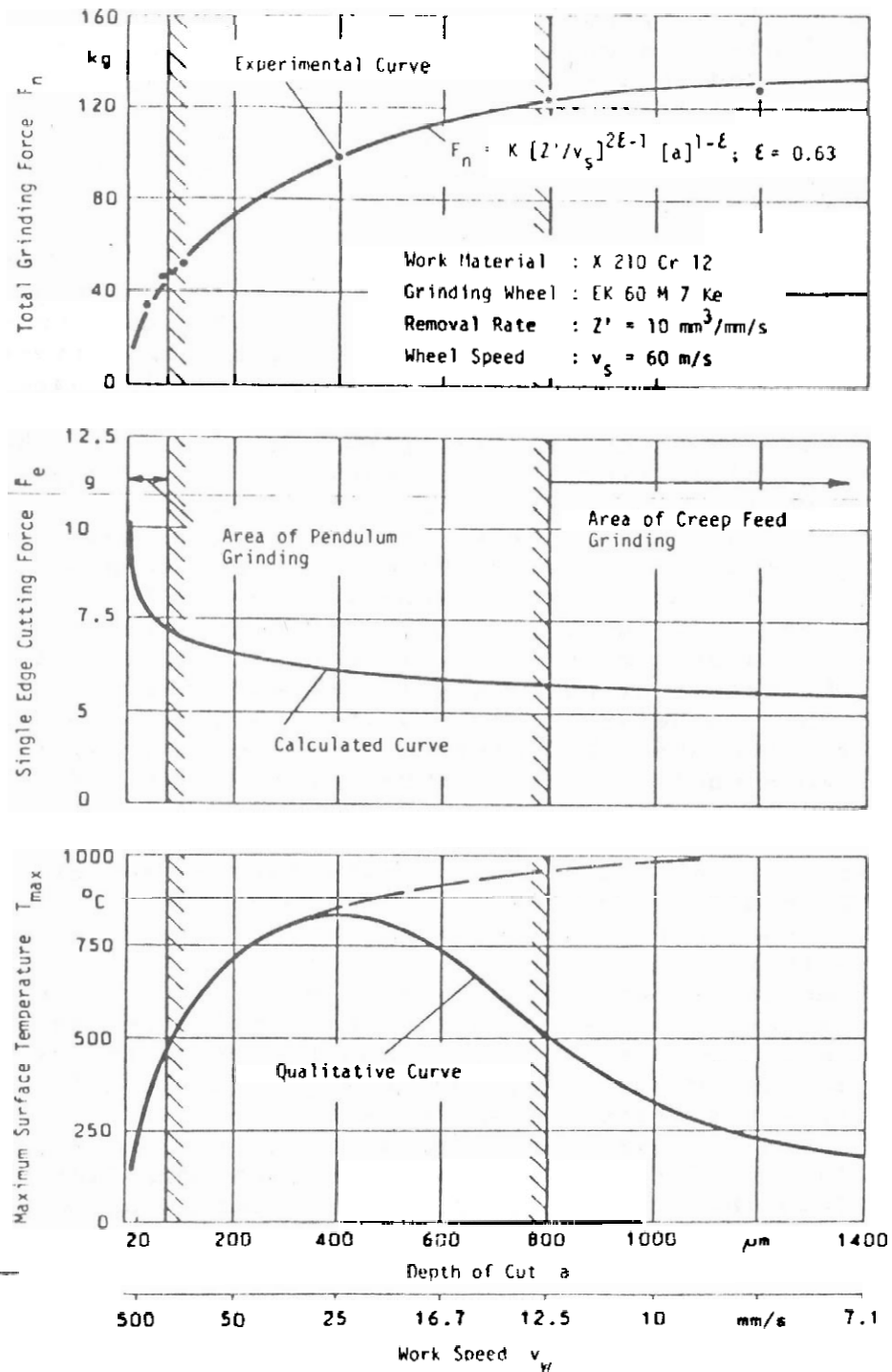


Figure 4: Behaviour of Grinding Forces and Work Surface Temperatures in Creep Feed and Pendulum Regimes /19/

Figure 4 illustrates the major technological differences between conventional pendulum and creep feed grinding. Total grinding forces, single edge cutting forces and maximum surface temperatures are plotted versus depth of cut and work speed. The specific removal rate Z' is the product of both the depth of cut and the work speed ($Z' = a \cdot v_w$), and it is kept constant. Thus, the left part of the diagrams represent pendulum conditions, whereas the right parts refer to creep feed conditions.

It is obvious, that the total grinding forces increase progressively with greater depth of cut. As a consequence, in creep feed grinding the power requirements and the machine stiffness must be significantly higher compared with conventional surface grinding machines. The reason for this specific characteristic is the much larger contact length between wheel and work piece at creep feed conditions. In strong contrast to this, the mean force per individual cutting edge decreases significantly versus depth of cut, and is much lower at creep feed conditions. As a consequence, wheels used for creep feed operations must show a reduced hardness, because otherwise the wheels tend to a glazing type of wear. In other words, the average load per cutting edge would not be high enough to secure the required steady state of wear. In practice this phenomenon is well recognized, however, the very reason why softer grinding wheels are necessary in creep feeding is not really understood. Mostly it is explained by the influence of a more open wheel structure as applied in creep feed grinding because more cooling fluid can be carried into and through the contact zone by such a wheel.

The most important prerequisite for the successful application of creep feed technique as an advanced manufacturing method is the very low thermal load as being induced into the surface layer of the work piece. Figure 4 shows, that the maximum surface temperature increases first with greater depth of cut, then it reaches a maximum, and towards the creep feed region decreases steadily. This observation seems to be in contradiction to the permanently increasing grinding force, indicating that the total energy consumed increases permanently, too versus depth of cut. However, with correspondingly lower work speeds the increasing amount of thermal energy flowing into the work surface, has more time to dissipate deeper into the work material. Thus, a larger amount of energy is effective in an even larger work volume, and results in reduced temperatures. If this specific mechanism would not be in effect then creep feed grinding would not be possible at all.

Figure 5 shows a modern surface Grinder specially designed for creep feed and pendulum operations /58/. This model has all features and characteristics necessary for creep feed operations as mentioned above. The work piece illustrated in Figure 6 is a

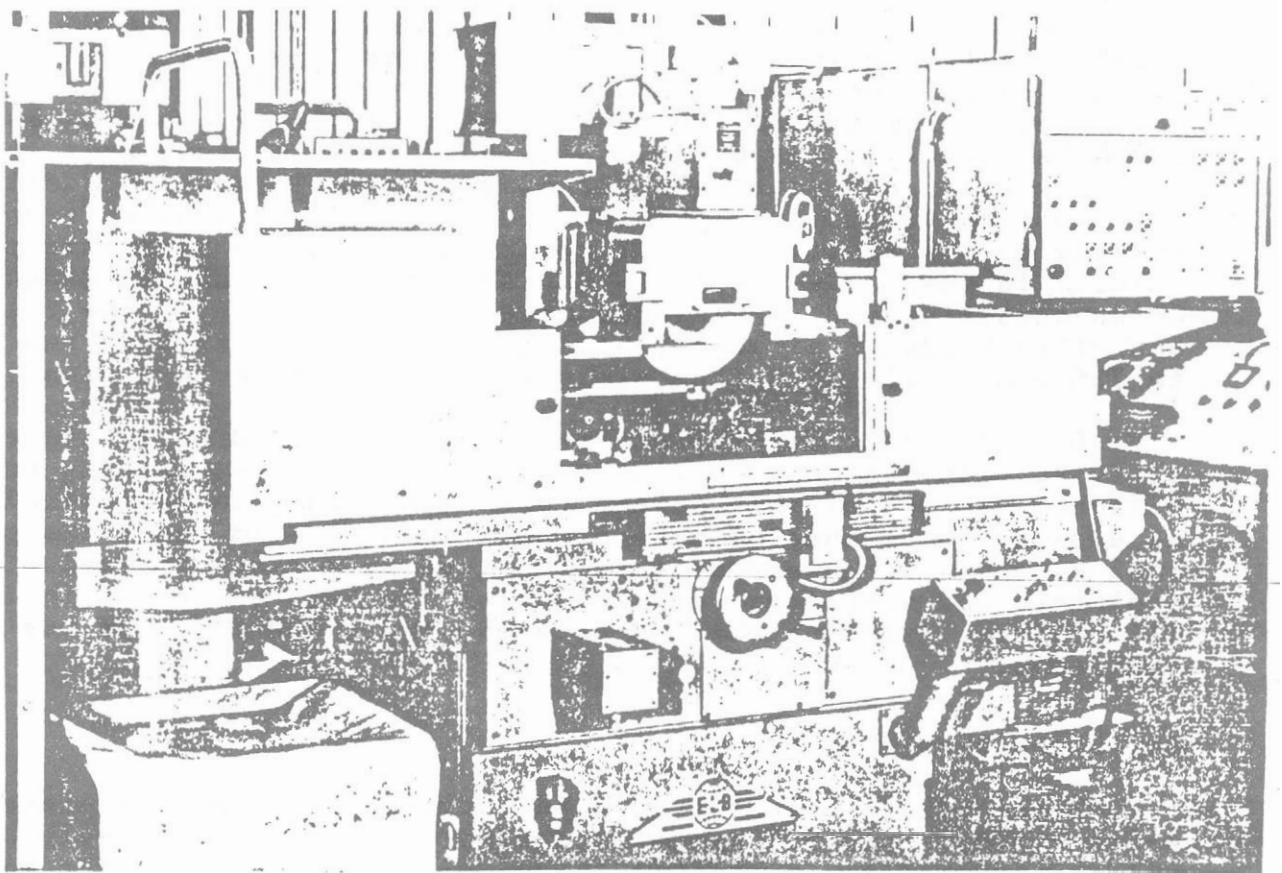


Figure 5:
ELB Creep Feed Grinder,
Type W08 /58/

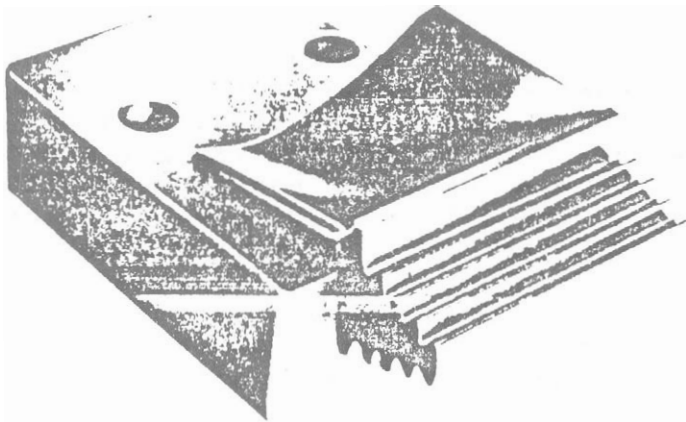


Figure 6:
Turbine Blade Ground by
Creep Feeding

typical example for creep feed application. Turbine blades like this made from nickel-cobalt-based superalloys are ground in one or two roughing passes and a subsequent finishing pass. Frequently both the profiles are cut at the same time by means of a double-disk creep feed grinder. The grinding wheels are dressed and profiled by high precision diamond roller dressing devices /44/. With work speeds less than 0.1 m/min (4 ipm) and oil or emulsion as coolants, a very good surface quality in terms of roughness, thermal integrity, and profile accuracy are accomplished. In addition the floor to floor times are reduced 25 to 50%. - Another frequent example is the slotting of air pressure rotors and hydraulic pump rotors. In these cases milling and subsequent finish grinding was often substituted by one single creep feed pass out of the full and often hardened material. Savings of machining time do run up to 75% especially when long slots with small widths are given.

One important constraint for creep feed grinding is its sensitivity with regard to deviations from the optimal working conditions. Because of this, creep feed technology can economically be applied only, when at mass production of suited parts the special know-how is generated and conserved by a group of dedicated engineers and operators, provided that the best equipment in form of machines, grinding wheels, dressing tools and fixtures are available.

IV. Speed Stroke Grinding

Speed stroke Grinding is a new surface grinding technique, which employs a normal pendulum surface grinder with a newly developed table drive system: A thyristor-controlled DC motor moves the work table back and forwards by means of a pre-tensioned gear belt. This system has a significantly higher degree of control, and as the crucial feature it provides a much higher table stroke rate at small stroke lengths. Thus it overcomes one of the major deficiencies of conventional hydraulic table drives, as they are in common use today /59/.

Figure 7 clearly demonstrates the superiority of the new method over the old technique: At a stroke length of $L_s < 50$ mm (2") a conventional hydraulic drive produces 30 strokes per minute. With the new speed stroke system up to 300 strokes per minute, that are 5 strokes per second, are achieved, and productivity is increased 10 times. Actually, the table speed is kept in the economic range above 10 m/min (30 fpm). With greater stroke length, i.e. larger work pieces, the differences in stroke rates are less pronounced, however, there is still a 30% advantage in this regime for speed stroke grinding to be used. As a second advantageous feature the grinding wheel is not fed stepwise after each pass

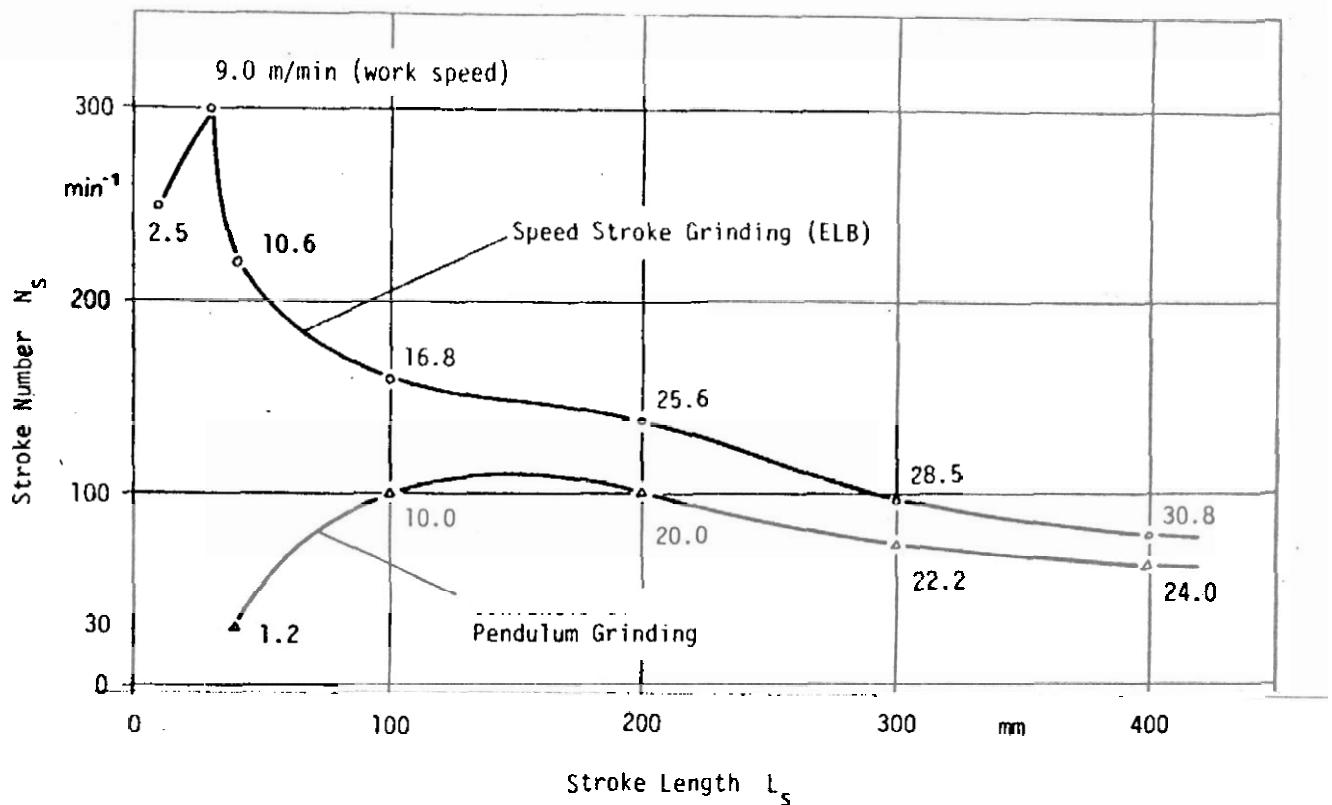


Figure 7: Stroke Rate versus Stroke Length for Speed Stroke and Conventional Conditions /59/

down into the work piece but moves in continuously. This infeed is automatically controlled in relation to the stroke rate such that the grinding wheel never comes out of contact with the work piece until the operation is finished. Thus, the contact shocks as effective in normal pendulum grinding at the beginning of each individual stroke, are eliminated in speed stroke grinding, resulting in a significantly reduced wheel wear.

Speed stroke grinding is best suited for grinding slots and profiles in small work pieces, and when the number of parts to be ground is small, as given normally in shop and tool room grinding. However, also for small and medium batch production of small work pieces it could become an economic alternative to creep feed grinding, because the machine is significantly less expensive, the technological know-how required with regard to grinding wheels and cooling fluids is rather conventional, the metal removal rates are equivalent or even better, and the speed stroke system needs less service and set-up time, than creep feed machines.

V. Cubic Boron Nitride (CBN) a New Abrasive Material

Cubic boron nitride is a crystal synthesized by a high-temperature / high-pressure treatment. Similar to the graphite-diamond transformation the hexagonal boron-nitride powder is thereby changed into the cubic CBN crystal. CBN is commercially available since 1969 as a GE product /55/, and was first used as abrasive material in form of resin bonded wheels for grinding of high speed and tool steels. More and more, however, CBN conquers the area of production grinding of superalloys, hardened steels of all kinds, and chilled cast iron. It has properties which are somehow similar to diamond, but some decisive minor differences (Table 1) result in completely different fields of applications for both of these so-called "superabrasives".

Diamond is by far the hardest material of all. Therefore it is predestinated to grind rigid-hard materials like sintered carbides, refractory materials, and granites. However, diamond is sensitive against elevated temperatures, especially in the presence of oxygen as always effective in normal grinding processes. In grinding the above mentioned rigid-hard materials the critical oxidation temperature of about 700°C is not reached. With ductile materials like soft or hardened steels, however, the effective chip formation temperatures are in the range of 1200°C and more. As a consequence, the hardest abrasive is not qualified to grind steels. CBN, however, has a much higher oxidation temperature and in spite of its lower hardness it is well suited to grind steels especially in the hardened state. Due to the lower hardness CBN on the other hand cannot effectively grind sintered carbides and other refractories.

In order to increase the application of CBN in production grinding two major obstacles must be overcome. The first one is a non-engineering problem: the extreme high price of CBN. With increasing usage there will be a good chance that prices go down. Competition, if encouraged, could help, too. The second problem is of mechanical nature: it is extremely difficult to dress and true CBN wheels to the required shapes and sharpness, especially when profiled wheels are used.

Property	CBN	Diamond	Al ₂ O ₃
Hardness [kp/mm ²]	4200	9000	2100
Decomposition Temperature [°C]	550	1400	2400
Oxidation Temperature [°C]	1300	700	—

Table 1: Hardness and Thermal Properties of Different Abrasives

The main problem still is, that after dressing with diamond dressing devices CBN wheels do not cut because the dressed surfaces of common resin and metal bonded wheels are completely closed and glazed. Only after a lengthy truing process is applied by treating the surface with a sintered Al_2O_3 stick for 30 to 60 minutes and more, depending on the wheel size, the BZN wheel might become sharp. This is an absolute impractical methode, which is rejected unanimously in industry.

Some recent developments seem to clear the way out of these difficulties. The first one is a metal bond of brittle character/44/ enabling to profile CBN and diamond grinding wheels by means of the well known crushing methode. A roller from hardened steel, sintered carbide, or though refractories, which possess the negative wheel profile, are forced into the revolving wheel, thus, working the positive into its perephery. Because of the very high grinding ratios ($G = \text{work material removed} / \text{worn wheel volume}$) those tools achieve, the loss of CBN grains during crush dressing can well be afforded. Figure 8 shows a crushing tool penetrating into a brittle bronze CBN wheel. Recent practical results, especially in creep feed grinding are extremely positive with regard to simplified dressing, achieved removal rates and grinding ratios, and the experienced profile accuracy and life time. The only minor disadvantage is, that metal bonded wheels generally show higher grinding temperatures, what has to be compensated by a well designed and properly applied cooling system /44/.

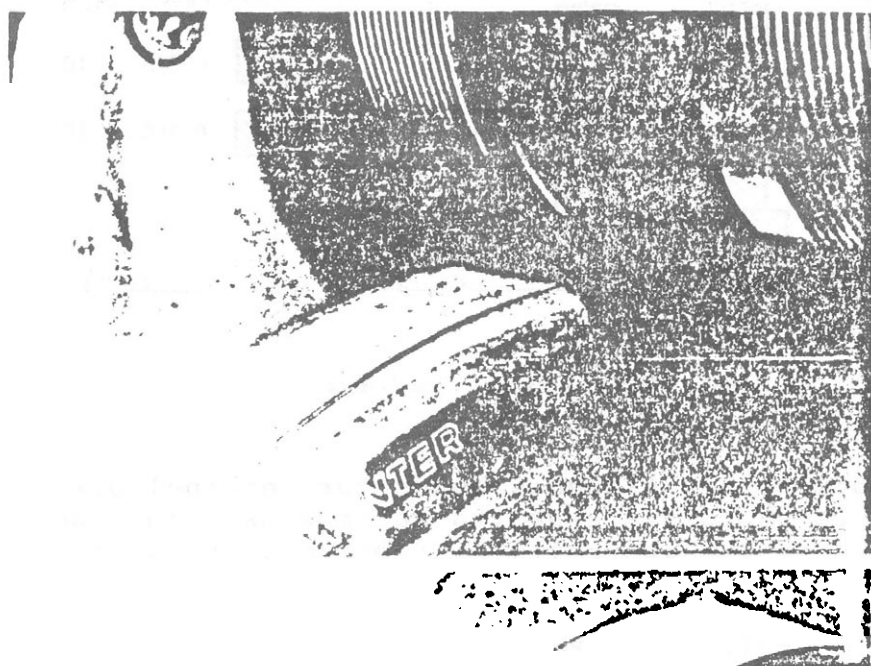


Figure 8:
Crush Dressing of a
Brittle Bronze CBN
Grinding Wheel /44/

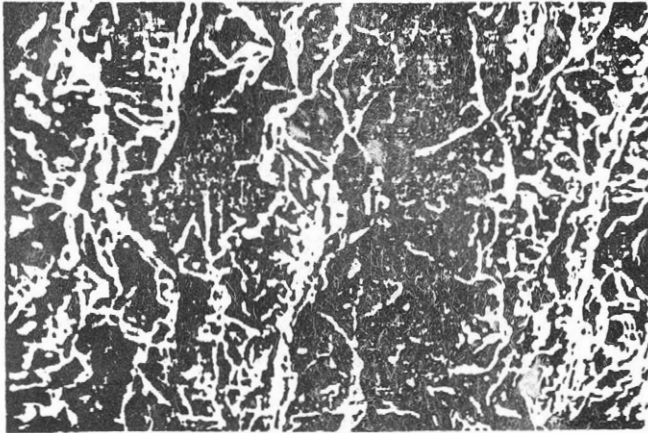
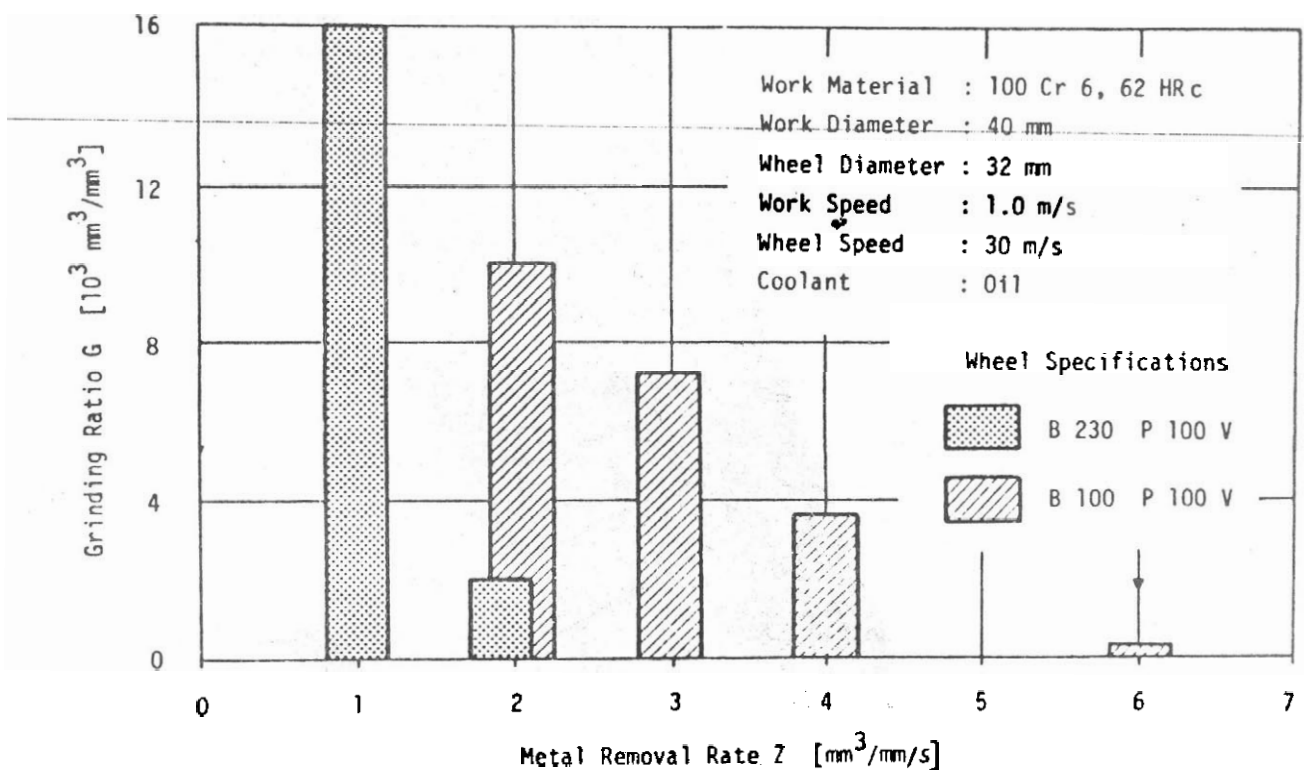


Figure 9:

Surface of Vitreous Bond CBN
Wheel for Internal Grinding
Operations /37/

Figure 10:

Grinding Ratios as Achieved
in Internal Grinding with
Vitreous Bond CBN Wheels /39/



The second novelty are vitreous bonds for internal grinding CBN wheels. Vitreous bonds are expected to provide a much better dressability, however, the conventional type requires a baking temperature near the decomposition temperature of CBN. This problem has been solved now by the development of a new glass-type of bond with significantly reduced processing temperature /45/. Figure 9 shows the dressed surface of such a CBN wheel. It has a

open appearance and cuts very free and cool /37/. As an additional advantage, the vitreous bond acts as an abrasive component, too, resulting in higher performance, controlled bond wear, and exceptionally good surface roughness. Figure 10 represents some results of recent investigations achieved at the Technical University in Hannover, West-Germany /39/. In internal grinding of hardened ball bearing steel these wheels showed extremely high grinding ratios of $G = 4000$ to 16000 , depending on the abrasive grit size and the applied metal removal rate. Obviously the system is sensitive against mechanical overloading, because the tests reveal a strong decreasing gradient of the G -ratio with higher removal rates, especially in the case of the finer grit size. Therefore these tools need a careful selection and control of the applied working parameters. During the tests all other conditions have been kept identical to conventional grinding with Al_2O_3 wheels. For dressing a specially designed, fast rotating, electro-plated cup-type of diamond tool has been used /45/.

It is very likely, that developments like these will in near future lead to a highly increased consumption of CBN abrasives in production grinding. Other areas of potential applications are gear grinding, thread grinding and centerless grinding.

VI. New Sensor for In-Process Detection of Work Surface Roughness

The work surface roughness is, besides the thermal integrity, the most important criterion of the working result in grinding. The only way, however, to check on surface roughness in production is to measure it externally by means of a conventional surface analyzer, which use a stylus to pick up a two-dimensional representation of the three-dimensional asperity distribution of the work surface. This on principle is a very slow process, because during measuring the effective profile frequency must be clearly below the natural frequency of the pick-up system to avoid over-riding.

A newly developed detection method turns things round and makes beneficial use of this disturbance by having a stylus responding in his natural frequency to the high and random frequency of a fast moving work surface. As a result the average stylus amplitude comes out as being proportional to the average asperity height of the work surface, and to the work speed /27/.

Figure 11 shows the system in principle. In the diagram at the right hand side the total roughness R and the center line average R_a as valid for different work surfaces are plotted against the recorded system out-put S . The constant work surface speed of 50 m/min is at the higher end of the range for conventional speeds

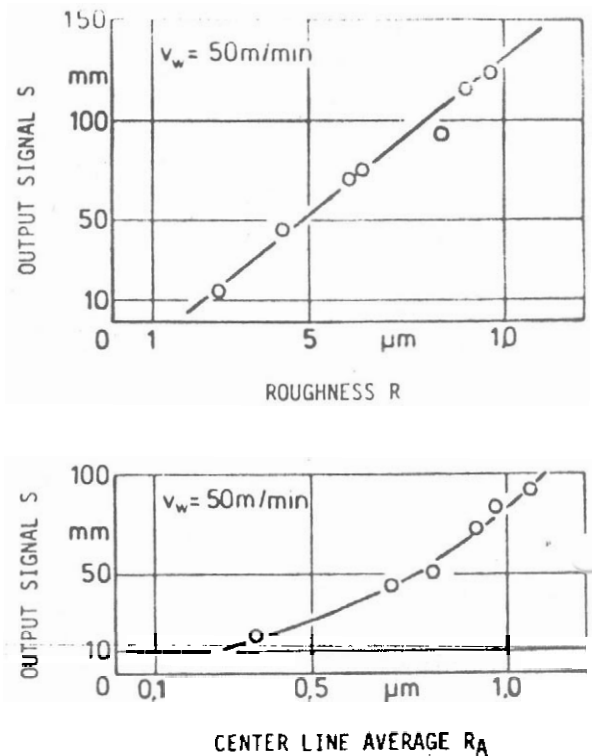
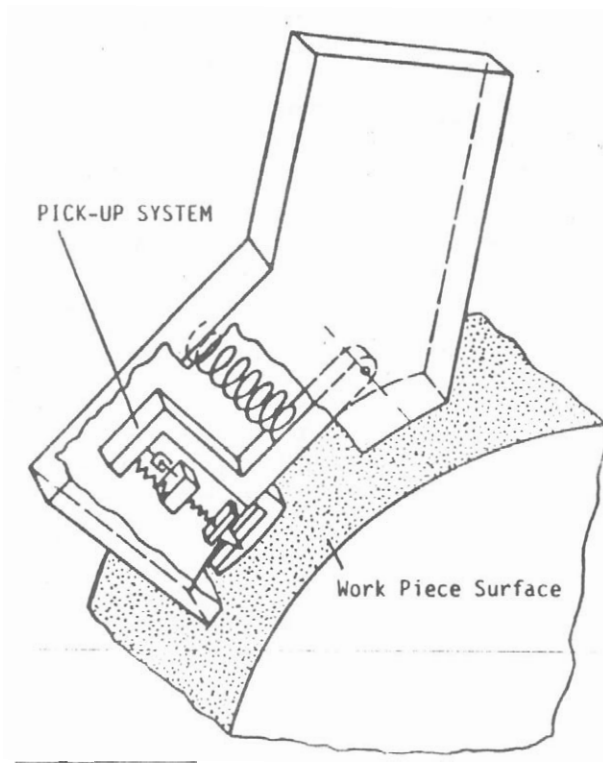


Figure 11: Principles of New Methode for Roughness Detection /27/

in external grinding, and it is more than 1000 times higher than applied with conventional roughness analyzers.

The new system was originally developed to work as an in-process sensor for an adaptive control (AC) external grinding system. It might, however, be of more immediately use as a module for in-process control of surface roughness in conventional external and centerless grinding operations. First practical experiences in production are being made actually at a major German automobile manufacturer.

VII. Electro-Sonic Determination of Grinding Wheel Hardness

Measuring the hardness of grinding wheels is an important operational process in wheel production and application. However, the traditionally used methodes were inaccurate and destructive to a certain degree. An example for this is the sand blasting methode where sand is blasted at defined rates, pressure and time onto the wheel surface, and the depth of the created hole is taken as a reference for the wheel hardness or softness respectively.

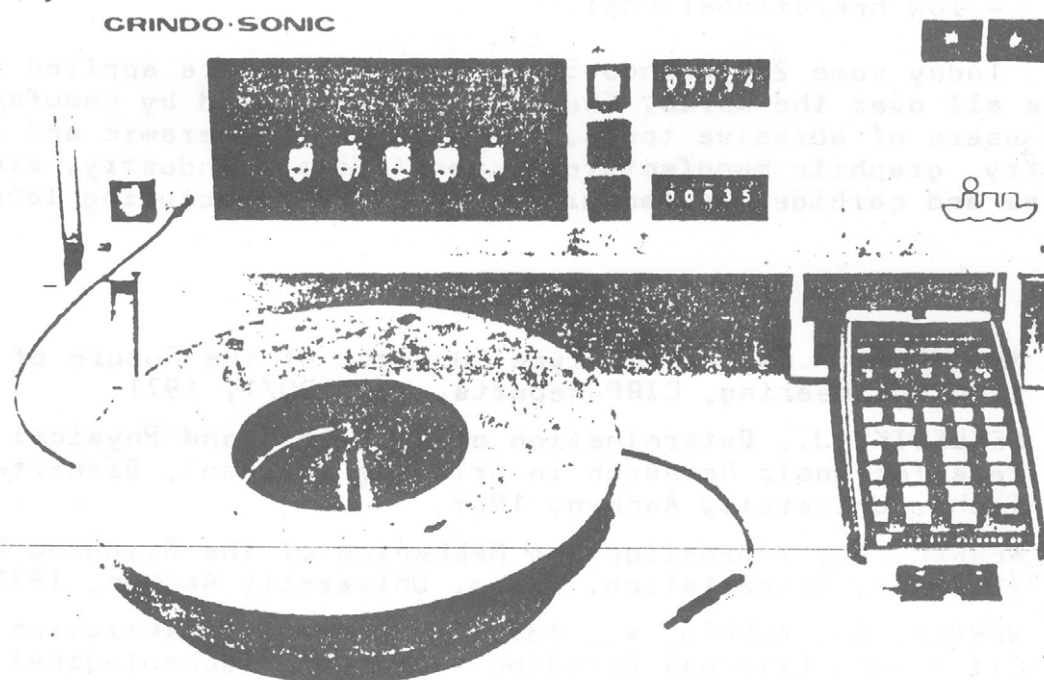


Figure 12: Grindo-Sonic Instrument for Wheel Hardness Testing /60/

Since 1970 a new non-destructive method, the Grindo-Sonic system / / is available (Figure 12), by means of which the hardness is determined from the elastic characteristics of the entire wheel volume. Actually, the grinding wheel or any other body like honing stones, sintered carbide parts or composite structures, are positioned such that they can vibrate free. Then after a slight impact with a screw-driver handle or a resin stick, the natural vibrations are picked up by a microphone and processed in a specially designed micro-logig unit. Taking the specific geometrical conditions into account, the hardness of the investigated body can be read from the display immediately. Some of the effective advantages are:

- 100% increased accuracy in hardness determination,
- Investigation on uniformity of structures possible by impacting different places,
- Same accuracy with large and small parts,
- Unlimited repeatability,
- Predominant consideration of the external structural volume,

- which are most relevant for the working hardness of grinding wheels,
- 100% checks are possible,
 - low operational cost.

Today some 200 Grindo-Sonic instruments are applied in practice all over the world. They are not only used by manufacturers and users of abrasive tools, but also in the ceramic and glass industry, graphite manufacturers, construction industry, sintered metal and carbide manufacturers, and in manufacturing laboratories.

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