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Elasticity modulus of grinding wheels and its impact on their in-process behavior

W. König / H. Föllinger

Teil 1 / Part 1

1. Introduction

The task of optimizing a grinding process that guarantees a successful outcome of the production step "grinding" includes the selection of suitable grinding wheels to meet the specified requirements. Even experienced grinders, however, sometimes have trouble making the proper choice. In addition to considering numerous relevant factors of influence, it must be kept in mind that the ginding-wheel nomenclature defined in West German standard specification (DIN) 69 100 offers no information from which direct conclusions could be drawn with regard to the in-process behavior of the tools involved.
In principle, this is because:
— the production processes used in making grinding wheels can differ substantially with respect to formula and procedures between one manufacturer and the next. Thus, while two grinding wheels may be of identical nomenclature, they can still show differences in tool behavior in an actual grinding process;
— it can be quite difficult to achieve consistent product quality due to raw-material quality scatter and the non-uniformities of screening, mixing, pressing and firing.
In view of the above, both the suppliers and the users of grinding wheels have a long-standing, vested interest in the development of test methods allowing:
— reliable monitoring of product quality and/for
— reliable forecasting of in-process tool behavior.
In the course of time, numerous test methods have been devised. Only few of them, however, have proven practicable to the point of gaining general acceptance by the industry. In addition to standard procedures like the Fuchs-Bosch, dynamic-pressure and Zeiss-Mackensen techniques, some test methods have been based on correlating the vibration behavior and hardness of abrasive compounds. Such so-called acoustic, or sonic, test methods include the Grindo-Sonic technique, which is used in determining the moduli of elasticity of grinding wheels.
High-coefficients of elasticity are indicative of "hard" grinding wheels. The Grindo-Sonic tester combines the main advantages of sonic testing, i.e.:
— objectivity and
— non-destructive measuring
with the additional advantages of
— low equipment expenditure and
— short measuring time.
At the same time, progress made in the field of test-instrument engineering has yielded better reproducibility of test results and improved handling characteristics.
Thanks mainly to the above merits, Grindo-Sonic testers have become firmly established among grinding-wheel manufacturers interested in thoroughgoing quality assurance. The quality data are arrived at on the basis of permissible tolerances for the elastic modulus of any given grinding wheel, with the tolerable bandwidth of deviation staying within a general magnitude of about $\pm$ 2.5 kN/mm².
Users, too, are showing an increasing tendency to judge the quality of incoming grinding wheels on the basis of their elastic moduli, as determined via receiving inspection. Understandably, the users would also like to be able to expand the control function to cover the probable in-process behavior of the tools. This would simplify the problem of comparing the quality of products from different manufacturers, thus lessoning the user's dependence on his "traditional" suppliers(s).
Consequently, both sides stand to gain much advantages from being able to predict the in-process behavior of grinding wheels on the basis of their elastic moduli. In that regard, however, the present situation is characterized by a substantial degree of uncertainty. This report is intended as a contribution toward eliminating such uncertainties.
As a point of departure, let us begin by examining the physical foundation of the Grindo-Sonic test method as a basis from which to proceed in evaluating the correlation between modulus of elasticity and the in-process behavior of grinding wheels, as discussed below.

Bedeutung des Elastizitätsmoduls von Schleifscheiben für ihr Verhalten im Schleifprozeß

W. König/H. Föllinger

Zur Auslegung eines optimalen Schleifprozesses, der den Erfolg des Fertigungsverfahrens Schleifen sicherstellt, gehört auch die Auswahl geeigneter, anforderungsgerechter Schleifscheiben. Diese Auswahl ist jedoch selbst für den erfahrenen Schleifer nicht immer einfach. Neben der Berücksichtigung einer Vielzahl relevanter Einflußfaktoren ist nämlich in Rechnung zu stellen, daß die Kennzeichnung von Schleifscheiben nach DIN 69 100 keine eindeutigen Rückschlüsse auf das zu erwartende Verhalten der Werkzeuge im Prozeß zuläßt.
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2. Physical fundamentals of the Grindo-Sonic test method

For testing, the grinding wheel is placed (not flanged) on four rubber cones arranged at 90° intervals (fig. 1). A plastic hammer is used to excite the grinding wheel by hitting it at a point situated between the cones. At the end of the transient period, the dominant mode of the wheel's bending oscillations is obtained in the form of a perforated disk, with the planes of maximum vibration amplitudes running between the points of support. The grinding wheel generates solid-borne noise that is picked up by a piezoelectric probe and passed on to the Grindo-Sonic unit. The tester examines the signal to determine the dominant-mode period. The value arrived at by the tester is indicated as the so-called R-value. The wheel's modulus of elasticity can then be calculated according to the equation developed by Peters, Snoeys and Decneut [1, 2] shown at center left in figure 1, bottom. The equation is based on the familiar physical causalities existing between the elastic modulus and the vibration behavior of a perforated disk made of

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These investigations were conducted with the kind support of the *Verein Deutscher Schleifmittelwerke e.V.* (VDS) and of the *Arbeitsgemeinschaft Industrieller Forschungsvereinigungen* (AIF), the latter by agency of the *Deutsche Keramische Gesellschaft*, through the resources of the *Bundesministerium für Wirtschaft*.

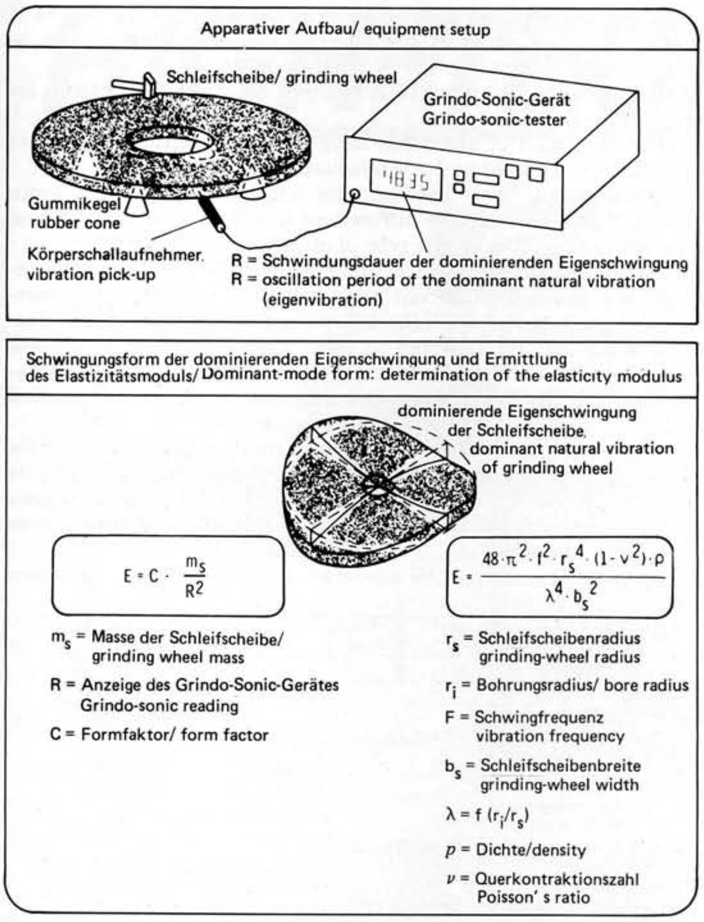

Abb. 1: Bestimmung des Elastizitätsmoduls von Schleifscheiben nach dem Grindo-Sonic-Verfahren
Fig. 1: Determining the elastic moduli of grinding wheels according to the Grindo-Sonic method

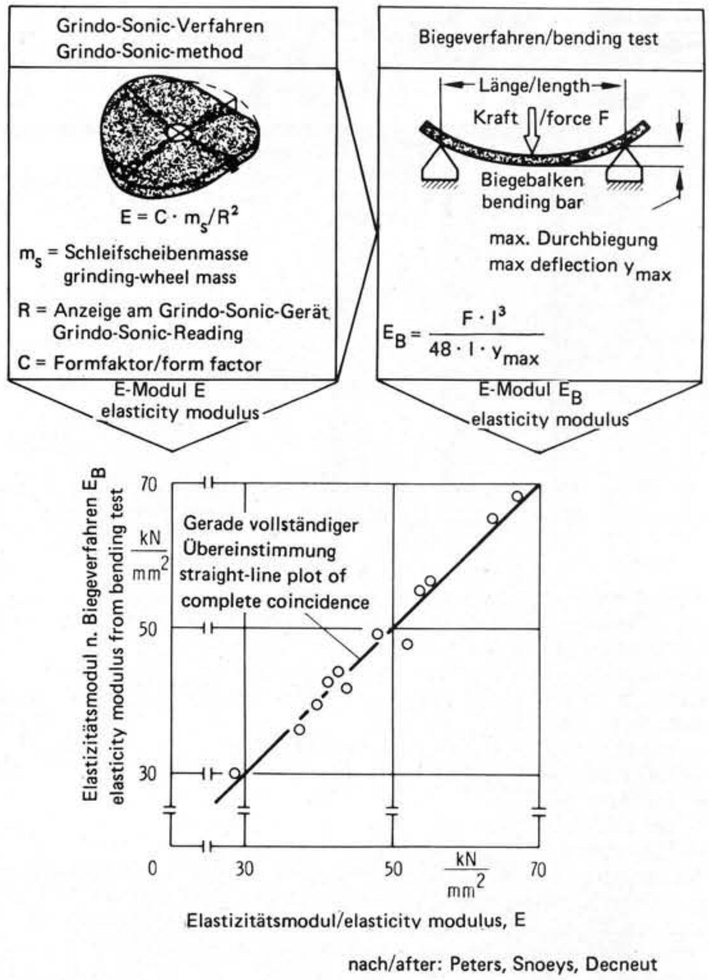

Abb. 2: Vergleich des nach dem Biege- und dem Grindo-Sonic-Verfahren ermittelten Elastizitätsmoduls
Fig. 2: Comparison of elastic modulus-values determined in bending tests and with a Grindo-Sonic tester

homogeneous material, represented by the equation shown at center right in figure 1, bottom.

This brings up the question of the extent to which an elastic modulus determined in the aforementioned manner corresponds to the "classical" elastic modulus dealt with in strength theory. The answer can be found by comparing values arrived at by calculating them successively from each fo the two formulae shown in figure 1, bottom.

First, the elastic moduli of grinding wheels were determined by the Grindo-Sonic method. Then, test specimens were cut out of the wheels and subjected to bending tests (configuration as shown at upper right in figure 2). Upon resolution of the lines-of-flexure differential equation, the maximum-deflection reading yields the specimen's modulus of elasticity. Comparison of the two values shows very good coincidence, with only minor deviations from the straigth-line plot, i.e. on the order of roughly 2.5 % [1, 2]. Once the basic aspects have been clarified, the expressiveness of elastic-modulus values with regard to the anticipated in-process behavior of the grinding wheels becomes accessible for investigation. By way of analogy to grindability testing, however, grinding-wheel behavior cannot be assessed according to some universal parameter, but requires consideration of several process-evaluation factors that directly or indirectly quantify the run of a given grinding process and the quality of the results of the process (fig. 3).

The grinding task at hand, upon which the investigations were based, was to plunge-cut a rectangular groove in a workpiece made of quenched and tempered high-speed steel S 6-5-2. The working depth, a_e, amounted to 1 mm. The down-grinding mode was chosen in order to keep the grinding temperature at a moderate level.

The specific tangential cutting force, F'_t, and the specific normal cutting force, F'_n, serve as quality factors for process evaluation by providing information on process temperatures, required power input and — via the machine's rigidity — dimensional accuracy and trueness of form.

With a view to cost reduction, high specific material removal rates, Q'_w, and/or specific material removal volumes, V'_w, are normally aspired to. Neither of those two parameters, however, can be increased indefinitely. Depending on the type of grinding to be performed, certain limiting criteria must be heeded, e.g. the avoidance of burnmarks or adherence to a certain maximum permissible workpiece surface roughness. Since such effects serve as equal-value limiting criteria, the achievable values for $Q'_{w, limes}$ and $V'_{w, limes}$ can be taken as a measure of grinding wheel performance.

The specific radial wheel wear rate, Q'_{sr}, and the worn-edge area, A_{Sk}, can serve as criteria for evaluating grinding wheel wear behavior. Of importance in that connection is that the parameter Q'_{sr} decouples the two main factors of influence that govern tool wear, namely load and time.

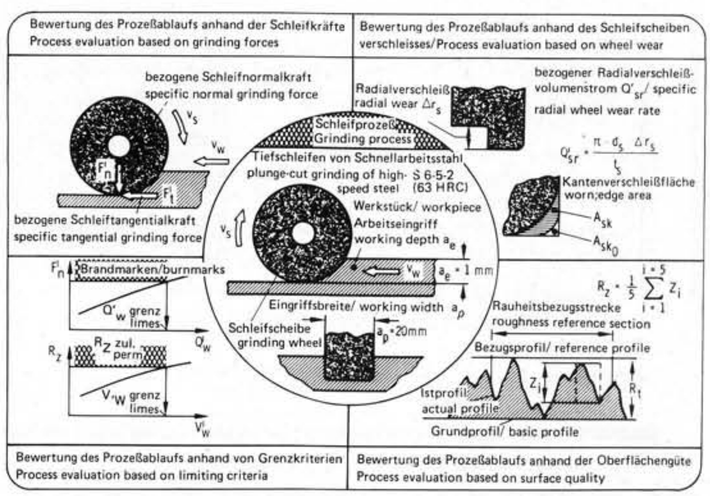

Abb. 3: Beurteilung des Ablaufs von Schleifprozessen anhand von Bewertungsgrößen
Fig. 3: Grinding-process evaluation based on quality variables

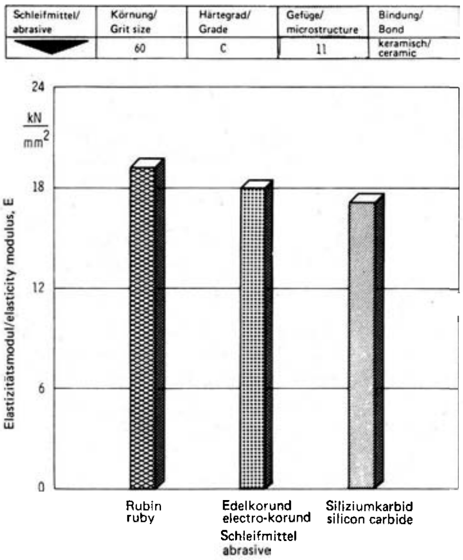

Abb. 4: Elastizitätsmodul von Schleifscheiben mit unterschiedlichem Schleifmittel
Fig. 4: Elasticity moduli of grinding wheels based on different abrasives

Also of value in assessing the in-process wear behavior of grinding wheels is the surface quality of the finished workpiece, as quantified by the mean peak-to-valley height, for example.
Any specification parameter with a bearing on the composition of grinding wheels also influences the in-process behavior of the tools. Such parameters include:

— the abrasive, i.e. the granular material
— its grain size
— its hardness
— the microstructure and
— the type of bond.

Assuming that only ceramic bonds are included in the investigations, the aforementioned objectives would dictate that the first four specification parameters be successively varied across broad value ranges and compared to the elastic modulus and to the process-quality variables.

3. The abrasive as an actuating variable

The question of how the abrasive affects the grinding wheel's elastic modulus and wear behavior can be approached by testing grinding wheels made of electro-corundum, ruby and silicon carbide, respectively, and then comparing the results with regard to elastic modulus, whereby the emerging differences are seen to remain insignificant (fig. 4).
According to the literature [2, 3, 4] there are two main reasons for such differences:
1. different types of abrasives have different particle shapes, so that the bond bridges and grain jackets also differ;
2. the transition layer between the bond bridge and the grain develops differently due to differences in chemical and crystalline structure, depending on the type of abrasive in use.
As the reader surely is aware, however, the aforementioned abrasives display totally different wear behavior, i.e. wearing properties. Consequently, even, light differences in the value of the elastic modulus can be expected to yield totally different in-process wheel behaviors. That behavior, together with the additional parameters grain size, hardness and microstructure, is exemplified below on the basis of process quality variables.
As expected, the ruby, electro-corundum and silicon-carbide wheels show completely different in-process behavior, despite only insignificant differences between their individual elastic moduli. This is illustrated in figure 5 with the aid of the process quality parameter $Q'_{w,\,limes}$.
The highest $Q'_{w,\,limes}$ can be achieved with the electro-corundum

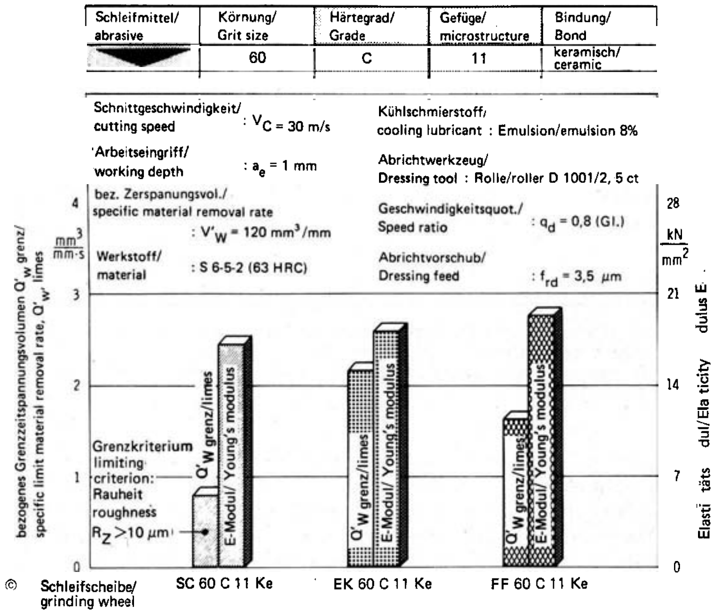

Abb. 5: Bezogenes Grenzzeitspannungsvolumen und Elastizitätsmodul von Schleifscheiben mit unterschiedlichen Schleifmitteln
Fig. 5: Specific limit material removal rates and elastic moduli for grinding wheels based on different abrasives

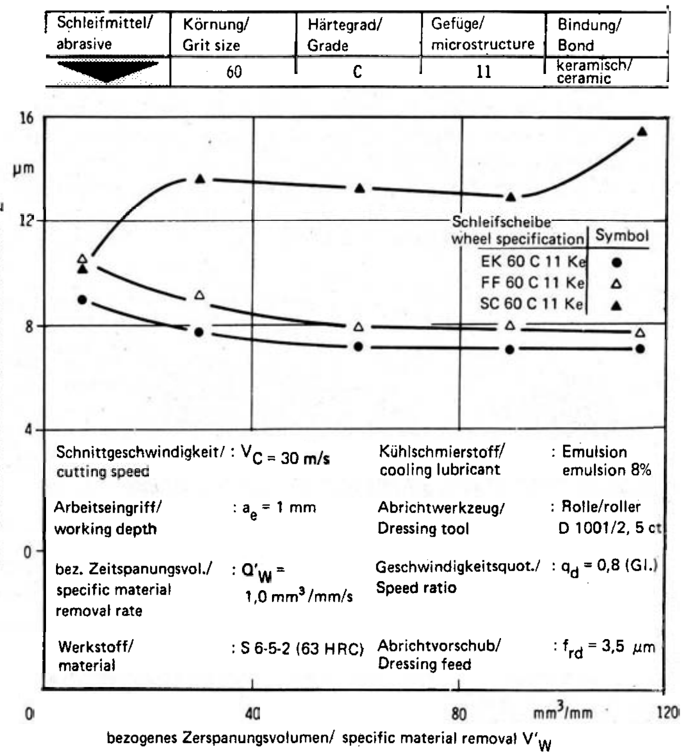

Abb. 6: Gemittelte Rauhtiefe in Abhängigkeit vom bezogenen Zerspanungsvolumen
Fig. 6: Mean peak-to-valley height as a function of specific material removal

wheel; it is significantly higher than that of the ruby wheel. Since ruby is tougher than electro-corundum, the grinding process leads to pronounced dulling of the indiviudal cutting edges on the ruby wheel. As a result, renewed contact between the dull grain and the workpiece produces disturbances in the process of chip formation, so that the contact-zone temperature increases. Consequently, the ruby wheel leaves burnmarks on the workpiece, even at a low cutting rate.
While "burnmark formation" therefore acts as a limiting criterion for working with electro-corundum and ruby wheels, the performance of the silicon-carbide grinding wheel was not limited by that problem, but by unacceptably high workpiece roughness values caused by failure of the tool's cutting face — an occurrence that came as surprising in view of the closely comparable elastic moduli. Plotting the mean peak-to-valley height, R_z, as a function of the specific material removal rate, however, confirms the correctness of the supposition (fig. 6).
All fHinding wheels produced mean peak-to-valley heights on the order of $9-10\ \mu m$ at the beginning of the grinding process, because the initial effective roughness values were all more or less equal due to identical dressing conditions.
As the grinding time progressed, the working faces of the electro-corundum and ruby wheels gradually became smoother due to grain attrition as the predominant form of microwear. Smoothing continued until a quasi-steady-state condition was reached, from which point on the mean peak-to-valley height was seen to

remain constant. The silicon-carbide wheel showed totally different in-process behavior. At first, the mean peak-to-valley height increased rapidly due to the aforementioned cutting-surface failure. As the grinding wheel's effective roughness height increased, the cutting forces decreased, allowing the cutting surface of the grinding wheel to restabilize. That, in turn, inevitably led to somewhat shallower peak-to-valley heights. Then, the again increasing cutting forces caused renewed failure of the cutting surface at a specific material removal volume of 90 mm³/mm.

Simultaneous consideration of all other process quality parameters as part of the analysis yields the following basic observation: It is not possible to forecast the in-process behavior of grinding wheels made of different materials solely on the basis of their respective elastic moduli, because the microwear behavior of the various abrasives has too much influence on the process quality variables.

(To be continued in cfi/Ber. DKG 8/9-87)

Aus der Praxis

Field Reports

High-tech ceramics and thick-film pastes

Erhard Korinth

Introduction

Thick-film pastes are, in effect, advanced versions of the long-familiar precious-metal decorating preparations for ceramics. As early as the late 19th century, attempts were made to exploit such preparations for technical purposes, e.g. by baking precious-metal preparations onto a ceramic substrate to produce electrically conducting paths. The 1898/1899 annual supplement to *Meyers Konversations-Lexikon* contained a report on how the Frankfurt-based manufacturing firm Prometheus applied thin-strip coatings of precious metal to porcelain enamel on steel to make "built-in hotplates" for cooking pots. The process involved "burning" normal brushable liquid bright gold, an organic gold compound in a dopelike solution, "into the enamel" at 900 °C. The simple heating-conducting network was arranged to yield four freely selectable heating stages.

In the opinion of the lexicon's editor, Prometheus cooking pots failed to gain much popularity because they used too much electricity — which at that time cost 16 pfennigs (now roughly 9 c) per kWh. Soon thereafter, experimental electric irons were designed around a heating system based on liquid bright gold applied to sheets of mica. Other companies began building direct-heated crucible furnaces and tube furnaces. But the problem was always the same: the brushed-on coatines/strips kept burning out at weak spots caused by irregular layer thicknesses. In addition, the electrical resistance values showed excessive scatter.

The invention of screen printing and its adaptation for ceramic decoration application techniques posed new opportunities for electronic engineers. The method employs uniformly woven, fine-mesh materials (sieve cloth) made of silk, nylon, polyester or steel and coated with photo-sensitive varnish. A diapositive is transferred by photo-technical means onto a coated cloth, thus producing a mask through which colors can be pressed with the aid of a squeegee. Assuming that the squeegee is handled carefully, a good screen mask yields uniform, reproducible prints.

With that technique in hand, it was possible to begin making series products displaying uniform resistance values.

While automakers seized upon the new technique for use in making heated rear windows, and appliance manufacturers applied it

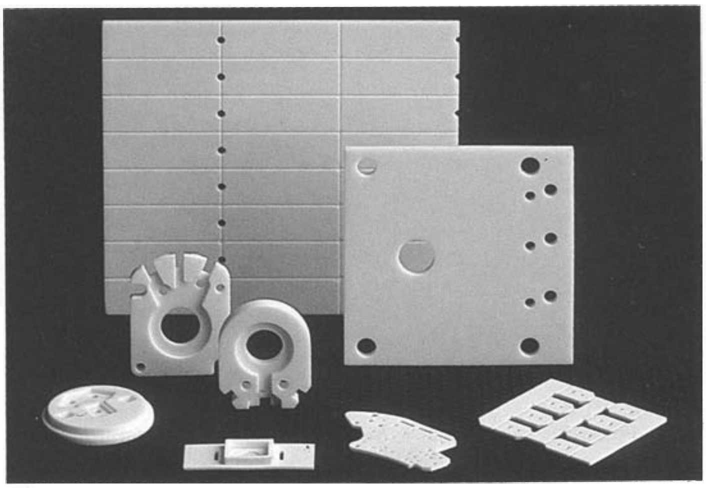

Abb. 1: Dickfilmsubstrate (Foto Hoechst CeramTec AG
Fig. 1: Thick-film substrates (photo by Hoechst CeramTec AG)

Dr. Erhard Korinth, c/o Degussa AG, Postfach 11 05 33, D-6000 Frankfurt 11

Paper presented on the 1986 DKG annual meeting in Wunsiedel, FRG.

Hochleistungskeramik und Dickfilmpasten

Erhard Korinth

Dickfilmpasten sind Weiterentwicklungen der seit langem bekannten Edelmetalldekorationspräparate für Keramik. Schon gegen Ende des vorigen Jahrhunderts wurde versucht, diese Präparate technisch zu nutzen. Man erzeugte elektrische Leiterbahnen durch Einbrennen von Edelmetallpräparaten auf keramischem Material. Viele Versuche folgten — immer aber ergab sich das gleiche Problem: der Pinselauftrag lieferte keine gleichmäßige Schichtdicke. Damit brannten dann die Heizleiter an den dünneren Stellen durch. Außerdem ergaben sich große Schwankungen im Widerstandswert.

Die Erfindung des Siebdrucks und sein Einsatz in der Keramik-Dekorationstechnik bot den Elektronikern eine neue Chance. Für diese Methode werden gleichmäßig gewebte feinmaschige Stoffe (Siebgewebe) aus Seide, Nylon, Polyester oder Stahl mit lichtempfindlichen Lacken beschichtet. Ein Diapositiv wird mit phototechnischen Mitteln auf das beschichtete Gewebe übertragen, so daß eine Schablone entsteht, durch die man mit einer Rakel Farbe pressen kann. Die gleichmäßige Siebschablone bringt bei präziser Rakelführung gleichmäßige und reproduzierbare Druckbilder.

Jetzt konnte man beginnen, Serienprodukte ohne Schwankungen im Widerstandswert herzustellen.

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Elastic modulus of grinding wheels and its impact on their in-process behavior

W. König / H. Föllinger

Teil 2 / Part 2

(Part 1 of this article was published in cfi/Ber. DKG 6/7-87, pp. 220)

4. Grain size as an actuating variable

When the size of the abraisve grain is taken as the second relevant specification parameter, the elastic modulus accurately reflects — under otherwise constant conditions — a gradual decline in hardness for an increasingly smaller grain size (fig. 7).
The indicated trend is attributable to the fact that the total surface area of the abrasive particles contained within a certain volume of the grinding wheel increases in inverse proportion to the grain size. In consequence, the share of so-called pseudo-bond increases. The term pseudo-bond is understood as the share of bond that builds no bridges and merely envelops the grain particles [3]. Since, however, the hardness of a grinding wheel is heavily dependent on the quantity, strength and length of the bond bridges, any increase in the amount of pseudo-bond necessarily leads to a loss of abrasive-body hardness. The vibration behavior of the grinding wheel shifts toward lower natural frequencies, resulting in a lower elastic modulus.
The loss of hardness is accompanied by an increase in the maximum achievable material removal rate (fig. 8).
The 80-grain wheel appears softer, an attribute which can be equated to grain popout as the dominant form of microwear. Since popout acts as a steady source of new, sharp cutting edges, the phenomenon has the effect of lowering the working temperature. Alternatively, the volume of material removed within a certain length of time can be increased to the point of burnmark formation.
Consideration of the causal relationships between the elastic modulus and the other process quality variables is deemed unnecessary at this point. The overall results, however, can be summed up as follows:
Using progressively finer grain automatically yields a higher share of so-called pseudo-bond, because the specific surface area of the abrasive particles increases accordingly. Consequently, the grinding wheel with the finer grain must be softer than a coarse-grained grinding wheel, even though their volumetric structures are identical. The loss of hardness is accurately reflected by the elastic modulus in connection with most process quality variables. However, no univocal link was found with regard to edge wear and workpiece roughness.

5. Wheel hardness as an actuating variable

By tradition, the definition of grinding-wheel hardness is based on how well an abrasive grain resists being torn out of its bond. Many manufacturers of grinding wheels vary the hardness of their products by using different amounts of bond while keeping the grain volume constant. Increasing the share of bond yields a larger number of bond bridges with larger cross sections, which naturally improves the bond strength.
But since the quantity, length and cross sections of the bond bridges affect not only the wheel's hardness in the sense of the standard definition, but also its vibration behavior, such a practice has the effect of increasing the elastic modulus with each successive grade letter (fig. 9), which characterize the wheel hardness.
According to the literature [1, 2, 3], the elastic modulus should change by about 4.5 kN/mm^2 per grade of hardness, thus indicating the linear relationship between the grade and the elastic modulus. It should be noted, however, that different grinding-wheel manufacturers can hold quite different views on assigning grade letters. Consequently, the relationship between the hardness of a grinding wheel and its elastic modulus need not always be linear.
The gain in hardness obtained by increasing the share of bond becomes conspicious when viewed in connection with certain process parameters, e.g. the specific cutting forces (fig. 10).
The higher holding power of the bond matrix in a grinding wheel exhibiting a high elastic modulus delays the popout of worn particles. While that does result in gradual dulling of the cutting surface, the grain particles are able to resist popout for a longer period of time, despite the resultantly high grain forces. Consequently, the overall level of specific grinding forces increases along with the elastic modulus.
Since comparably good correlations exist between the elastic modulus and the other process quality parameters, the overall results boil down to the following conclusions:
As long as the hardness, or grade, of a grinding wheel is determined by its bond fraction, the elastic modulus will serve as a sufficiently accurate tool in forecasting the wheel's in-process behavior. All process quality parameters plainly correlate with the elastic modulus.

Bedeutung des Elastizitätsmoduls von Schleifscheiben für ihr Verhalten im Schleifprozeß

W. König / H. Föllinger

Teil 2

Zur Auslegung eines optimalen Schleifprozesses, der den Erfolg des Fertigungsverfahrens Schleifen sicherstellt, gehört auch die Auswahl geeigneter, anforderungsgerechter Schleifscheiben. Diese Auswahl ist jedoch selbst für den erfahrenen Schleifer nicht immer einfach. Neben der Berücksichtigung einer Vielzahl relevanter Einflußfaktoren ist nämlich in Rechnung zu stellen, daß die Kennzeichnung von Schleifscheiben nach DIN 69 100 keine eindeutigen Rückschlüsse auf das zu erwartende Verhalten der Werkzeuge im Prozeß zuläßt.
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Schleifmittel/ abrasive	Körnung/ Grit size	Härtegrad/ Grade	Gefüge/ microstructure	Bindung/ Bond
Edelkorund/ electro corundum	▼	L	15	keramisch/ ceramic

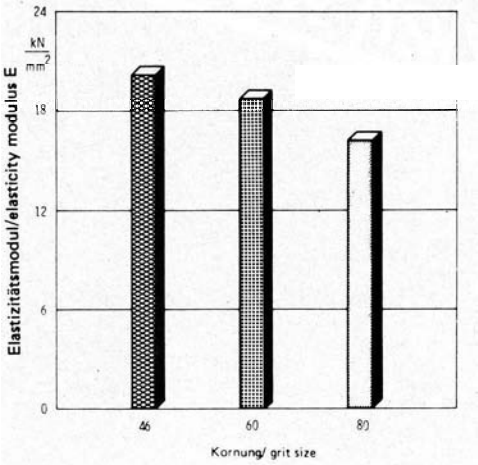


Abb. 7: Elastizitätsmodul von Schleifscheiben unterschiedlicher Körnung
Fig. 7: Elasticity moduli of grinding wheels with different grain sizes

Schleifmittel abrasive	Körnung Grit size	Härtegrad Grade	Gefüge microstructure	Bindung Bond
Edelkorund electro corundum	▼	L	15	keramisch ceramic

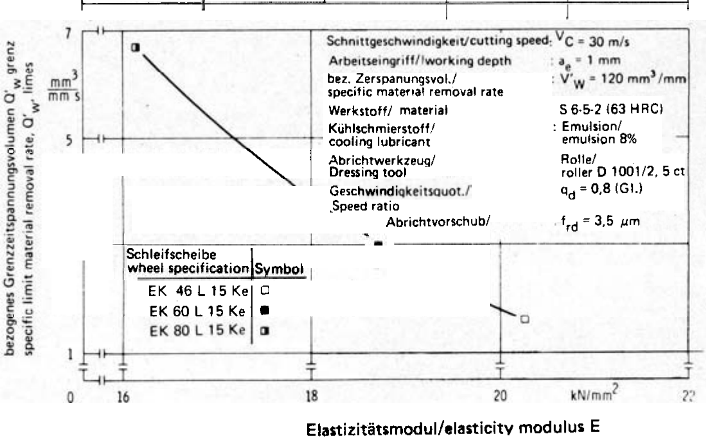


Abb. 8: Einfluß des Elastizitätsmoduls von Schleifscheiben unterschiedlicher Körnung auf das bezogene Grenzzeitspannungsvolumen
Fig. 8: Specific limit material removal rate as a function of elasticity modulus for grinding wheels with different grain sizes

Schleifmittel/ abrasive	Körnung/ Grit size	Härtegrad/ Grade	Gefüge/ microstructure	Bindung/ Bond
Edelkorund/ electro corundum	60	▼	11	keramisch/ ceramic

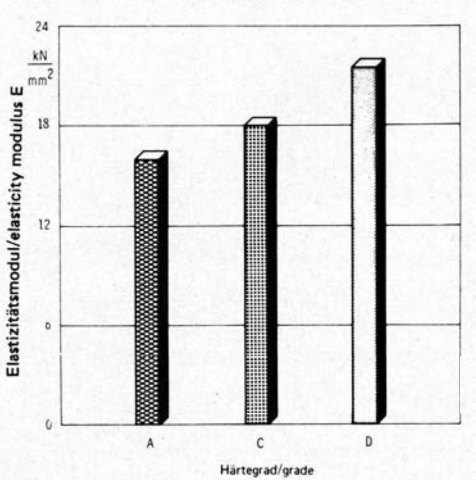


Abb. 9: Elastizitätsmodul von Schleifscheiben unterschiedlichen Härtegrades
Fig. 9: Elasticity moduli of grinding wheels displaying various degrees of hardness (grade)

6. Grinding-wheel microstructure as an actuating variable

The effective hardness of a grinding wheel is directly determined by its abrasive microstructure, i.e. the volumetric composition and distribution of abrasive particles, bond and pore volume. The microstructure is characterized by a series of numbers ranging from 0 to 14, with 0 indicating a closed microstructure and 14 indicating a very open microstructure. The most frequently employed way to vary the structure is to change the grain-volume percentage; open structures are obtained for low grain-volume percentages.

Schleifmittel/ abrasive	Körnung/ Grit size	Härtegrad/ Grade	Gefüge/ microstructure	Bindung/ Bond
Edelkorund/ electro corundum	60	▼	11	keramisch/ ceramic

Schnittgeschwindigkeit/ cutting speed : V_C = 30 m/s
Kühlschmierstoff/ cooling lubricant : Emulsion emulsion 8%
Arbeitseingriff/ working depth a_- = 1 mm
Abrichtwerkzeug/ Dressing tool : Rolle/roller D 1001/2, 5 ct
bez. Zeitspanungsvol./ specific material removal rate : Q'_W = 1,0 mm³/mm/s
Geschwindigkeitsquot./ Speed ratio : q_d = 0,8 (Gl.)
Werkstoff/ material : S 6-5-2 (63 HRC)
Abrichtvorschub/ Dressing feed : f_{rd} = 3,5 µm

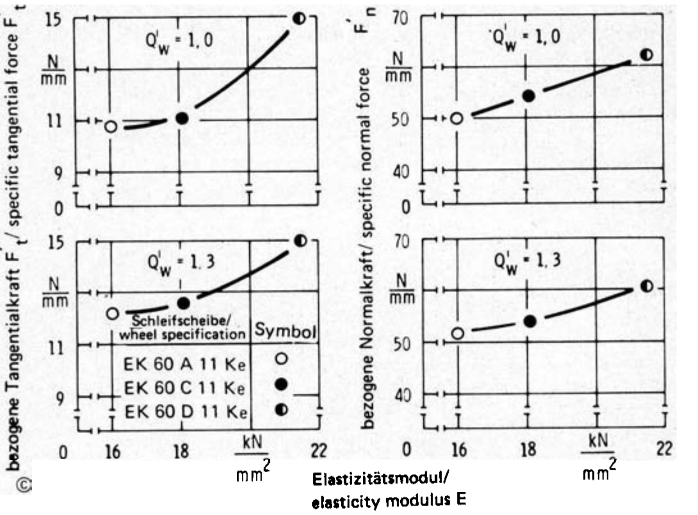


Abb. 10: Einfluß des Elastizitätsmoduls von Schleifscheiben unterschiedlicher Härte auf die bezogenen Schleifkräfte
Fig. 10: Specific grinding forces as functions of the elasticity modulus of grinding wheels displaying different degrees of hardness (grade)

The more open the structure, the lower the elastic modulus of the grinding wheel (fig. 11).
The relatively large intergranular distances in an open structure automatically lead to longer and — on the average — thinner bond bridges, so that the fatigue behavior shifts toward lower natural frequencies and, hence, a lower elastic modulus.

Schleifmittel/ abrasive	Körnung/ Grit size	Härtegrad/ Grade	Gefüge/ microstructure	Bindung/ Bond
Edelkorund/ electro corundum	60	C	▼	keramisch/ ceramic

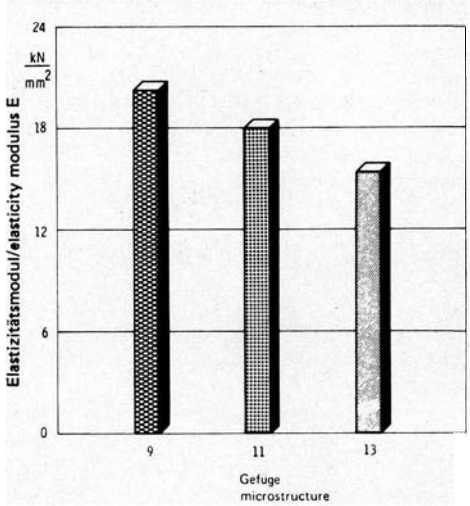


Abb. 11: Elastizitätsmodul von Schleifscheiben mit unterschiedlichem Gefüge
Fig. 11: Elastic moduli of grinding wheels with different microstructures

A low structure number equates to a high number of static and, hence, kinematic cutting edges, so that relatively high specific cutting forces can be anticipated. As shown in figure 12, the cutting forces actually do increase, as expected, as a function of the elastic modulus.
The large number of cutting edges per unit of area provided by a

closed tool structure produces chips with shallow thicknesses. Material removal therefore involves more friction/displacement phenomena in the contact zone. The combination of ineffective energy conversion and large quantity of cutting edges acting on the workpiece at any given moment makes the specific grinding forces increase progressively, as indicated in the figure-12 diagrams.

In the sense of interim evaluation, however, it should be noted that the grinding wheels studied in these investigations were all of relatively similar structure. With that in mind, the findings — with due respect to all process quality parameters — can be summarized as follows:

Among grinding wheels of relatively similar microstructure, most process quality parameters can be estimated accurately enough for technical purposes as functions of the elastic modulus. There are, however, no definite correlations with respect to the worn-edge area and workpiece roughness.

Up to this point, the relationship between the elastic modulus and the various process quality variables has been characterized by varying only one specification parameter at a time. Accordingly, the findings apply only to the discrete areas in which any change in the properties of a grinding wheel occurs as the result of a single measure.

Thus, systematic analysis must include determination of the effects of changing two ore more specification parameters at once. Moreover, in order to achieve a higher level of analytical efficiency, the following considerations can be built into the procedural approach. The question of central interest is whether or not the formula for an electro-corundum grinding wheel can be manipulated such as to yield a nearly constant elastic modulus in combination with an as yet unforeseen type of in-process behavior. The specifications dealt with in figure 13 can serve in finding the answer.

The EK 60 L 15 Ke-type and EK 60 D 6 Ke-type grinding wheels have identical elastic moduli. At the same time, the EK 60 L 15 Ke-wheel is characterized by a very open microstructure with a low grain-volume fraction and the highest bond volume fraction. The 6, standing for microstructure, shows that the EK 60 D 6 Ke-wheel has a closed microstructure. Its high density is chiefly the result of a high grain-volume percentage. This wheel contains the lowest amount of bond. The EK 60 G 11 Ke-wheel structure fits in between those of the other two.

Despite close coincidence between the elastic moduli, the wheels display extreme differences in in-process behavior, as indicated by the process quality parameter $Q'_{w,\,limes}$ (fig. 14).

The limiting criterion "burnmark formation" cannot be applied to the EK 60 D 6 Ke-wheel, i.e.. the one with the highest Q'_w values, because its low bond fraction makes it so soft that high specific material removal volumes lead to failure of the abrasive face and a high level of workpiece roughness instead of producing burnmarks. Consequently, as in the case of the silicon-carbide wheel, transgression of the maximum permissible mean peak-to-valley height, R_z, (10 µm) serves as the limiting criterion.

The very porous EK 60 L 15 Ke-wheel has the lowest limit for specific material removal. Its high bond fraction is concentrated on the lowest number of abrasive particles, thus enhancing the wheel's nominal hardness. That, in turn, leads to burnmark formation, even at low loads, i.e. low Q'_w-values.

These findings, which can be further substantiated by way of the other process quality parameters, lead to the following conclusion: The expressiveness of elastic-modulus values with regard to anticipated in-process grinding behavior is most limited in cases where grinding wheels displaying extreme microstructural differences are compared. In no such case is the elastic modulus capable of adequately reflecting the effective hardness of the wheels in question.

7. Global significance of the elastic modulus

Recapitulatory analysis of the interdependences dealt with above shows that the significance of the elastic modulus can be substantially impaired with respect to the in-process behavior of grinding wheels. In extreme cases, it could even lead to false conclusion. On the other hand, univocal correlations can usually be established between the elastic modulus and the process quality variables by modifying only one specification parameter at a time and limiting the scope of analysis to that parameter.

However, the central question is — or should be — to which extent the general in-process behavior of grinding wheels can be

Schleifmittel/ abrasive	Körnung/ Grit size	Härtegrad/ Grade	Gefüge/ microstructure	Bindung/ Bond
Edelkorund/ electro corundum	60	C		keramisch/ ceramic

Schnittgeschwindigkeit/ cutting speed : v_c = 30 m/s
Arbeitseingriff/ working depth : a_e = 1 mm
bez. Zerspanungsvol./ specific material removal rate : V'_w = 120 mm³/mm
Werkstoff/ material : S 6-5-2 (63 HRC)
Kühlschmierstoff/ cooling lubricant : Emulsion/emulsion 8%
Abrichtwerkzeug/ Dressing tool : Rolle/roller D 1001/2, 5 ct
Geschwindigkeitsquot./ Speed ratio : q_d = 0,8 (Gl.)
Abrichtvorschub/ Dressing feed : f_{rd} = 3,5 µm

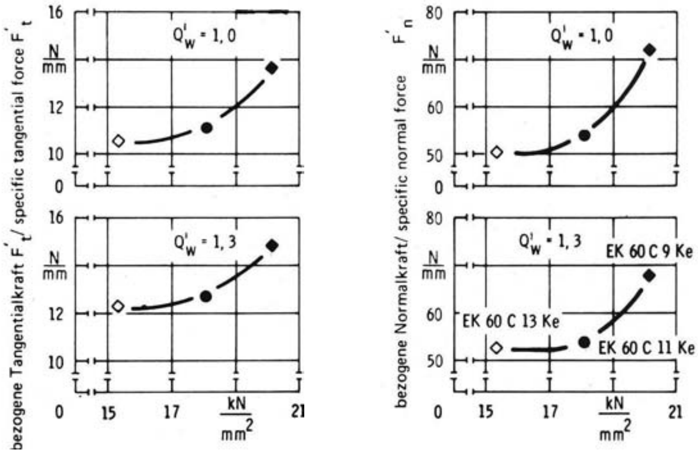
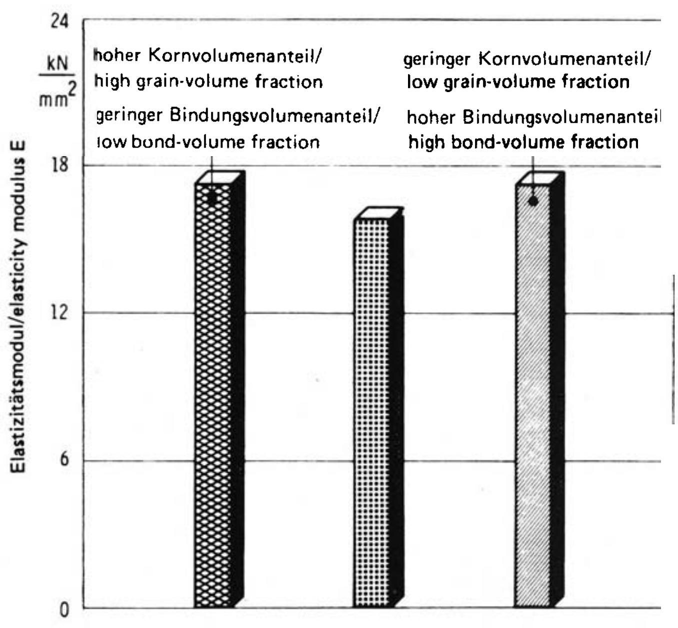


Abb. 12: Einfluß des Elastizitätsmoduls von Schleifscheiben mit unterschiedlichem Gefügeaufbau auf die bezogenen Schleifkräfte
Fig. 12: Specific grinding forces as functions of the elastic modulus of grinding wheels with different microstructures

predicted with the aid of their respective elastic moduli, i.e. independently of which and how many specification parameters are varied or from which manufacturer the wheels are obtained.

Thus, in order to pin down the global significance of the elastic modulus, all of the grinding wheels included in the investigation

Schleifmittel/ abrasive	Körnung/ Grit size	Härtegrad/ Grade	Gefüge/ microstructure	Bindung/ Bond
Edelkorund/ electro corundum	60			keramisch/ ceramic



Schleifscheibe/ wheel specification : EK 60 D 6 Ke · EK 60 G 11 Ke EK 60 L 15 Ke

Abb. 13: Nahezu konstanter Elastizitätsmodul trotz extremer Unterschiede in der Schleifscheibenzusammensetzung
Fig. 13: Near coincidence of elasticity moduli despite extreme differences in grinding-wheel composition

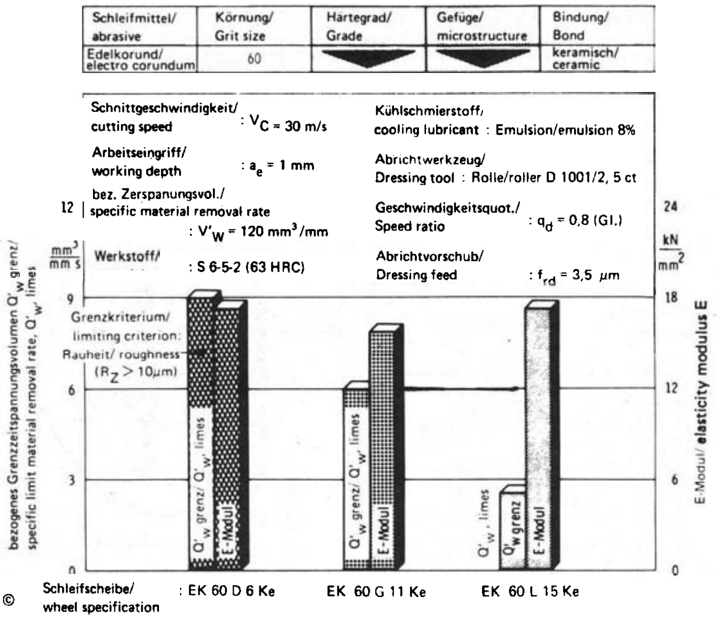


Abb. 14: Bezogenes Grenzzeitspannungsvolumen und Elastizitätsmodul von Schleifscheiben mit extrem unterschiedlicher Zusammensetzung
Fig. 14: Specific limit material removal rates and elasticity moduli of grinding wheels displaying extreme differences in composition

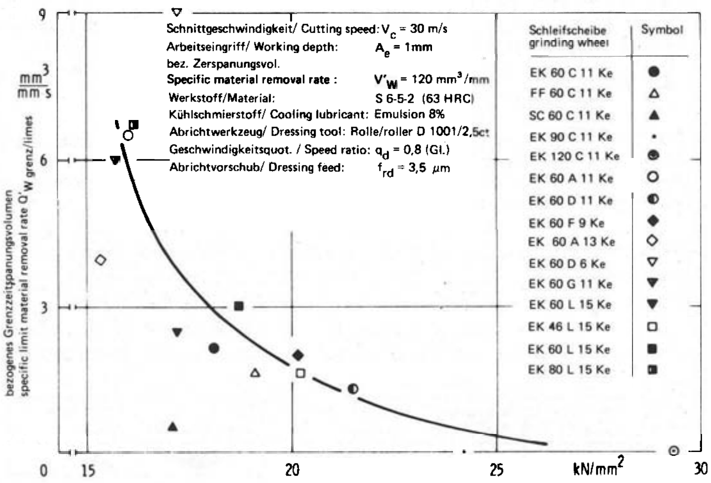


Abb. 15: Einfluß des Elastizitätsmoduls von Schleifscheiben auf das bezogene Grenzzeitspannungsvolumen
Fig. 15: Specific limit material removal rate as a function of the elastic moduli of grinding wheels

must be directly compared with each other, in which case the only correlations to emerge are those existing between the elastic modulus and the process quality variables $Q'_{w,\,limes}$ and $V'_{w,\,limes}$ as exemplified for $Q'_{w,\,limes}$ in figure 15.
Interpretation of the described connection is deemed unnecessary in this context, since the various causes of the subject trend have already been dealt with repeatedly and in detail.
The fact is that the power of expression of an elastic modulus is so limited as to preclude univocal description of a tool's in-process behavior independently of the formula and/or the employed production techniques. On the other hand, the product quality of mutually similar grinding wheels can be monitored relatively simply and inexpensively by way of the elastic modulus.

8. Summary

The purpose of these investigations was to ascertain the significance of the elastic modulus with respect to the in-process behavior of grinding wheels.
The results obtained through extensive variation of the grinding-wheel specification parameters "abrasive", "grain size", "grade" (hardness), and "microstructure" can — for wheels of mutually similar volumetric structure — be reduced to the following observations:
— The effects of different abrasive materials on the process itself and on the results obtained cannot be adequately forecast on the basis of the elastic modulus.
— In most cases involving electro-corundum grinding wheels, varying one specification parameter at a time, e.g. grain size, yields good correlation between the process quality variables and the elastic modulus. To be sure, the results apply only to the extent to which the tool's properties have been influenced by a singular measure, e.g. by modifying the effective hardness by way of grain-size variation.
— As soon as comparisons between the elastic modulus and the process quality variables are drawn without dependence on how changes in tool properties are effected, correlations are obtained only for $Q'_{w,\,limes}$ and $V'_{w,\,limes}$.

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