

# IDEAL AND REAL MICROSTRUCTURE SYSTEMS OF SOLIDS\*

By

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## Introduction

Owing to recent epochal changes which took place in the last decades on the Earth we are obliged by necessity to raise other requirements concerning the quality and use of materials. The industrial development prior to and after the second world war, the rapid growth of population and the ever more observable exhaustion of non-reproducible natural energy sources, furthermore the recognition of the limited nature of reserves and of the role of social and environmental interactions created a novel situation for the development according to the established concepts. At a population whose number and demands are increasing and at a decreasing reserve of raw materials the continuation of the living conditions of mankind — at a materialistic level already attained at other places — can be ensured only by products of extremely good quality, reliability and durability.

The prerequisite of the recognition, choice and production of such materials is an exact knowledge of the relationship between structure and properties.

According to our practical experience throughout the world products at very varying levels and quality, despite the fact that all production technologies are aimed at and have the object of manufacturing in a reproducible way products of the best quality possible.

In a number of industrial branches countries and manufacturers are known which and who predominate on a given territory by the good and constant quality of their products. The leading role of these manufacturers is due to the fact that they possess relatively precise knowledge and adequate possibilities for producing their products in a definite and reproducible quality and they use in fact these possibilities.

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### Structure of the Solids

The properties of the material are determined by its structure whose definition has been composed as follows:

The structure or structure types of the material are forming an interrelated system starting from being built-up from the smallest particles to the macroscopic appearance. The structures are, by type and in the complex system of components built up on each other, entireties of a great number of structural elements linked to each other by type and also by their entirety in a defined way.

As components of these structures the followings must be taken into account:

- type of particles participating in the build-up,
- their properties,
- their dimensions,
- their ratio,
- the way of their linkage,
- and their interactions.

Structure systems will be discussed in the followings as microstructure, and they will be treated here expediently from the lowest limit known thus far to the limit of resolution by optical microscope.

It must be mentioned still that the measure of the dependence of properties of the material on microstructure in the widest and general sense may vary from property to property and may extend from full independence to extreme sensitivity.

First of all we must accept as a verifiable fact that the solid material is, in any form of its appearance, lastly from the aspect of structure not to be considered as non-arranged, irregular.

However, the mode and measure of arrangement are varying.

Obviously, the "arranged properties" expected from the materials can be ensured only by adequately arranged structures.

The general system of recognition and evaluation of arrangement means in addition to the thus far already more or less known fundamental regularities of structural build-up also the outlining of the logical sequence of the coherent, arranging forces which are determining the matching order of the structural elements of varying dimensions and the outlining of the correlation of these forces.

If the structure of the material is determined by the type, properties, dimensions, ratio and way of linkage of the participant particles, the recognition and presentation of the structural types which are starting from the atomic building up and are directed towards the macroscopic structure is of primary

importance for the knowledge of the relationships between the structural building-up and the properties.

First of all the own properties of the particles of which the material and the elements consist, respectively, must be known. For this work the periodic table of the elements serves as a basis of systematizing.

The next step is the recognition of the regularities governing the spatial arrangement of atoms, ions or groups of atoms. Meanwhile we are entering the domain of crystalline substances.

Lastly, the investigation of the relationships between the microstructure of materials of one phase or of several phases and arranged to different measures and developed under natural or artificial conditions, and their properties is of decisive importance from practical aspects. This investigation differs from those mentioned above in its nature, its methods and its complexity since, owing to the heterogeneous composition and structure, the properties of the "pure" compounds and individual particles are mostly already (or still!) hardly recognizable in the whole material.

The properties of the solid mass follow from the entirety of the structure and interactions of the individual particles. The relationship between the structure of the individual particles and the properties of the mass is very complex and in many cases still not surveyable.

The grades of the structural building-up of solid materials are as follows, on emphasizing the role of "scale changes".

Factors determining the fundamental properties of the solid material are summarized in Fig. 1.

The more and more finer structure of the atom can be studied in the way shown in Fig. 2, by means of the interactions of the components of atoms with known particles with higher energy.

The properties of the elements are determined by their periodically constructed electron structure.

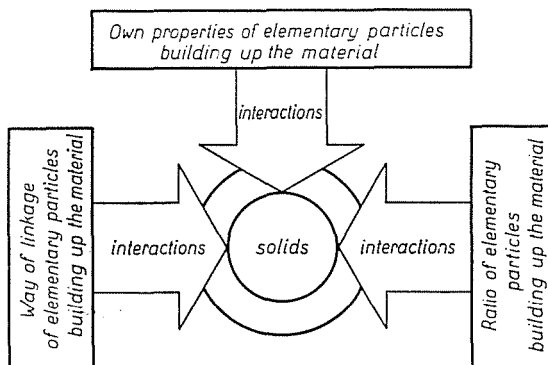


Fig. 1. Correlation of factors determining the fundamental properties of solids

The electron structure of the elements is, with the exception of the noble gases, no stable formation under ordinary conditions. Thus, the elements strive for attaining a more stable state.

The individual properties of the atoms, molecules and atomic groups are already not recognizable in the mass by their interactions because their structure changes, the chemical bonds are split and newer localizable or non-localizable molecular levels are created.

On the effect of forces acting between atoms, molecules and atomic groups the above mentioned building elements are arranged.

From the aspect of the knowledge of the *relationships between the building-up and properties of solid materials* in 1912 the X-ray diffraction experiment of *Max von Laue* and co-workers *W. Friedrich* and *P. Knipping* of decisive importance (Fig. 3):

The diffractogram obtained on photosensitive paper reflects the intrinsic structural pattern of the crystal which pattern can be described in various

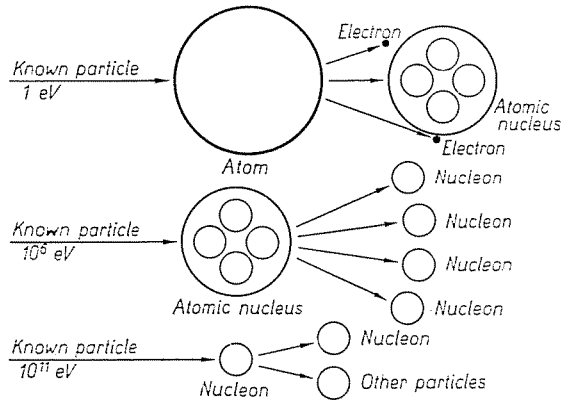


Fig. 2. The recognized structure of materials

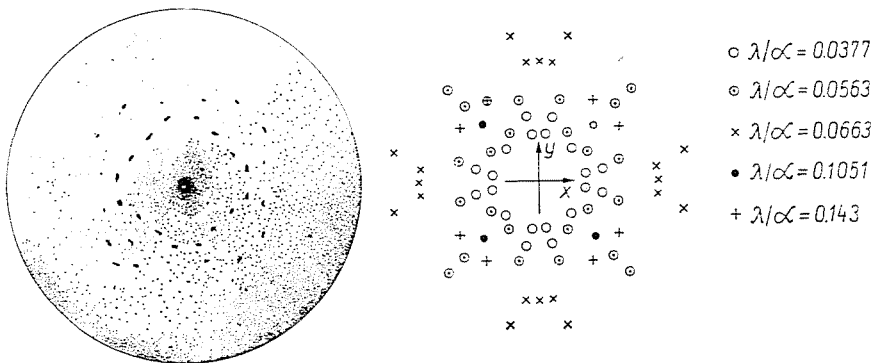


Fig. 3. One of the original X-ray diffractogram made by M. von Laue and co-workers

ways e.g. as a mathematical equation. On side of this equations is a function describing in detail the intrinsic structural patterns of the crystalline material whereas the other side expresses how the former function depends on the diffraction effects.

If the inner structure of the crystal is known, the diffractogram can be established in advance. When however, all the diffraction data are known, the crystalline building-up can be established.

Besides the crystalline substances the amorphous materials are typical representatives of solid materials.

Investigation of solid substances by X-rays cleared up to a great extent the essence of not only the crystalline state but also of the amorphous state. These investigations indicated that the amorphous and crystalline substances do not represent two in principle different states but denote rather different degrees of the arrangement of building blocks which degrees are linked to each other by continuous transitions. Though the crystalline state requires basically a strict spatial arrangement of building blocks whereas these are located irregularly in the amorphous substances, the crystals indicate on the one hand many deviations from the ideal order and approximate the amorphous state, and the amorphous substances may attain on the other hand an arrangement of very high order which approaches the crystalline state.

Thus the amorphous state embraces a very big domain: from the non-arranged molecular state to the pseudocrystalline clusters disclosing a high degree of regularity. The smallest atomic groups of the most solid amorphous substances are completely identical with those of crystals though their linkage does not show the repeatability which characterizes the crystalline state. Consequently amorphous substances of this type are in a small part of their space "semi-crystalline" but in a greater part of their space statistically irregular clusters.

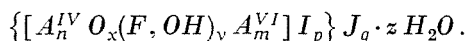
On the basis of the topological structure characteristics of crystalline compounds they can be classified into three types of microstructures. Besides the periodicity extending to three dimensions some microstructures consist in one dimension, others in two dimensions whereas again other in three dimensions of more closely linked infinite atom bundles. In the second or third dimensions, in turn, the bundles are linked often to each other loosely and at greater periods. The one-, two- and three-dimensional linkage leads at the same time to fundamental differences in the properties. All the three types of crystalline regularity have pseudocrystalline, amorphous varieties as well.

The overall formula of crystalline compounds does not reflect precisely the properties of these compounds. In order to be able to express unequivocally the properties of the compound, besides the nature and ratio of the atoms also their structural position must be indicated in their formula. Owing to the manifoldness and complexity of crystal structures it is impossible to denote

the whole structure at an adequate shortness. However, on the basis of certain previous agreement concerning the way of describing the formula it is possible to denote the main features of the structural position of atoms (their coordination environment). The formula described in this way is known as the crystal-chemical formula of the compound wherein the structural position, quality and ratio of atoms are denoted in a combined way.

In the crystal-chemical formula great stress must be laid upon the environment of the cations in a way that the cations in tetrahedral and octahedral coordinations which are in the most crystal structures anyhow in a privileged position are sharply distinguished from each other, furthermore those cations which occur in a coordination environment higher than octahedral and as a rule irregular.

On taking these in considerations the crystal-chemical formula of compounds is written down as follows: The cation present in a tetrahedral (eventually lower) coordination ( $A^{IV}$ ) occupies the first place followed immediately by the whole amount of the anion. This is mostly oxygen but can be partly also F or OH. After the anion, the cation in octahedral environment ( $A^{VI}$ ) is written down. The above mentioned part of the formula is then put in parentheses to separate it from the inactive (I) cations and lastly the eventually present molecular water is denoted. If necessary, also the inactive anions (J) must be denoted (e.g. in ultramarines) outside of the square brackets. In the most general case thus the composition of e.g. the silicates and of many other oxygenous compounds can be expressed by the formula



Of the symbols (subscripts)  $y$ ,  $n$ ,  $m$ ,  $p$ ,  $q$  and  $z$  any may be equal to zero, and thus the structural formula can be simplified to a great extent.

The crystal-chemical formula of crystalline compounds complemented by the symbols of the crystal class and of the spatial group comprises the general features of the structural building up.

The perfect crystals wherein the atoms, ions or molecules are located in the whole macroscopic body according to a strict inner order, can be considered only as ideal limit cases.

### Investigation of the Ideal and Real Crystal Structure

The typical energetical-morphological differences due to building up of the ideal and real crystal structures can be developed and studied also directly by etching.

A number of chemical and physical changes can be employed for etching; all that is required is that the process should remove the material evenly

from the surface and not create a damaged surface. The basic etching processes are the following:

- (a) Chemical. The material is caused to undergo a chemical change under the condition that the reaction products leave the surface.
- (b) Electrolytic. Electric current is necessary to cause dissolution of the material in a suitable electrolyte.
- (c) Alloying. Molten metals can be used as etchants by virtue of their ability to take certain solid materials into solution — a process commonly known as alloying.
- (d) Cathodic bombardment. The material is made the cathode in a glow discharge. The energy of the bombarding ions drives the atoms of the material off the surface.
- (e) Thermal. The material is heated to a high temperature in a vacuum or in an inert atmosphere; etching is accomplished by vaporization.
- (f) Solvation. The etchant is a liquid acting as a solvent of the material being etched.

Particularly the chemical etching is suitable, owing to its simplicity, selectivity and rapidity, for the recognition of the symmetry properties of the crystal lattice or e.g. the presence, formation, movement etc. of the dislocations.

By means of chemical etchings almost perfect crystal surfaces, equilibrium surface configurations possessing the thermodynamically minimum energy, the symmetric conditions of the crystals and the properties relating to them can be investigated in a relatively simple way. A number of phenomenological theories (e.g. that of Frank etc.) deal with the formation of the equilibrial morphology. In the case of nearly perfect crystals (which may be found among e.g. the semiconductors) their validity can be controlled also by experimental methods. This has been proved also e.g. in the case of a Ge crystals (Fig. 4).

It was attempted relatively early to use, besides the surface of crystals on the effect of the etching agent (or of the unsaturated vapour space), also

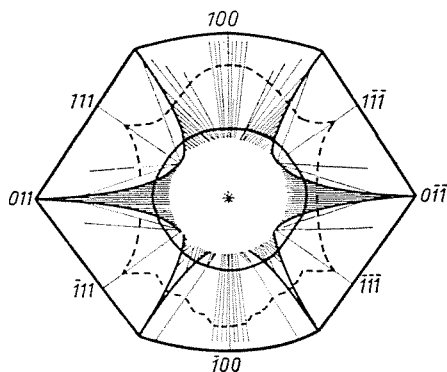
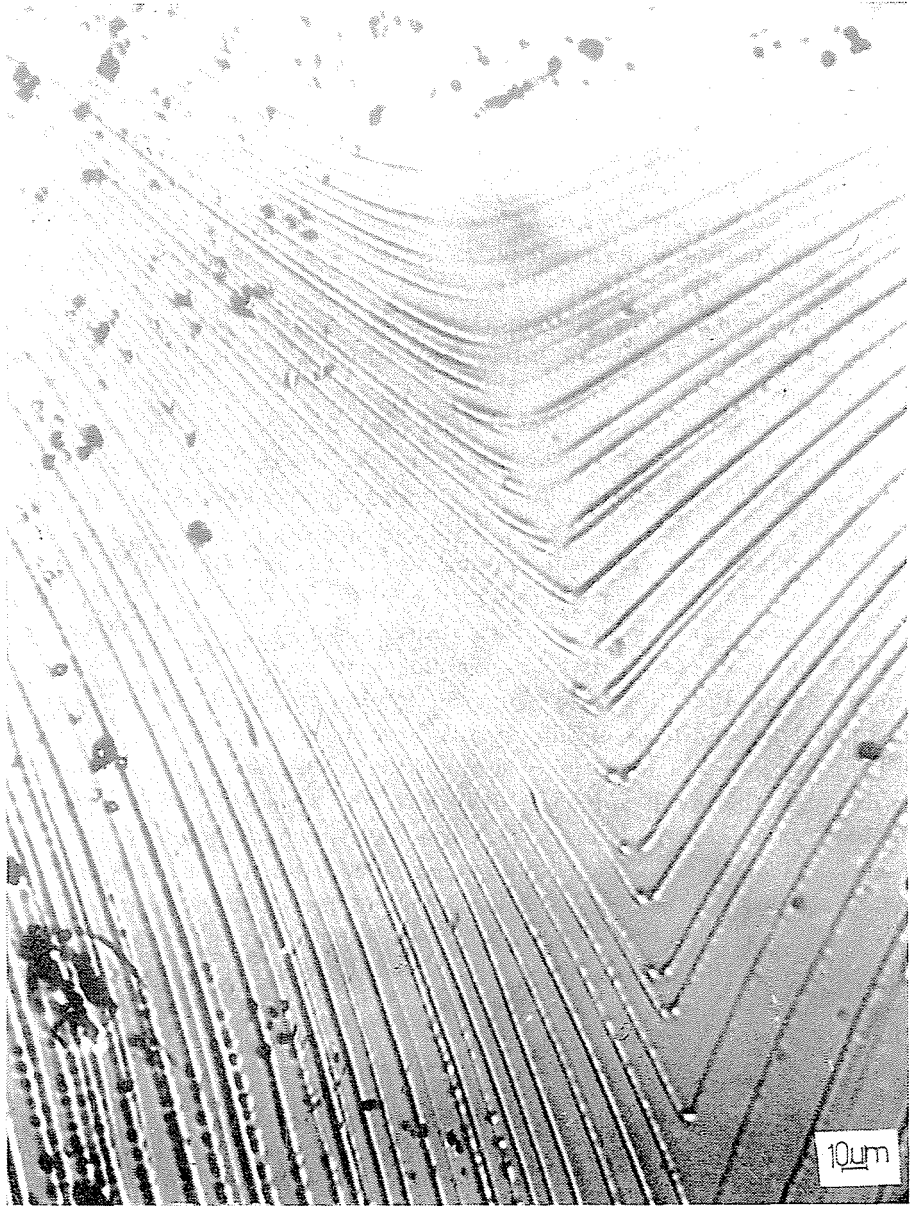


Fig. 4. Construction of the etching shape of germanium on the basis of the Frank model



*Fig. 5.* Micrographs by light microscope of the etched surface of grinding grains of silicon carbide



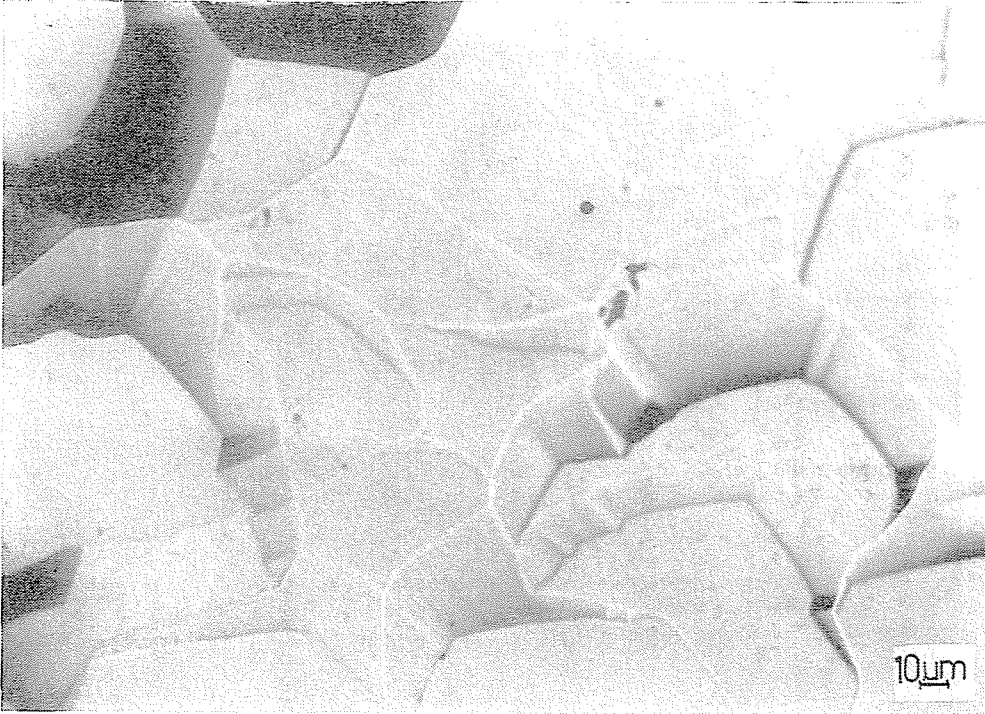


Fig. 6. Micrographs by light microscope of the etched surface of grinding grains of silicon carbide

the etching pits developed on the surface and often disclosing a high symmetry, for the study of the microstructure of crystals. On studying the structure of the grain boundaries of the crystals it was found that e.g. in the grain boundaries of small angles the distance of the dislocations is satisfactory even for the microscopic observation of the individual dislocations provided an adequate chemical developing is applied. This could be proved similarly on a germanium single-crystal. Namely, in a germanium single-crystal the difference of orientation calculated from the X-ray diffraction measurements agreed very closely with that calculated on the basis of the model from the distance of the etching pits.

In accordance with data of literature we have succeeded in detecting the direct relationship between the dislocations and the etching pits in our chosen and particularly investigated model substance: SiC, in which on applying an adequate etching agent, etching pits in fact were formed at the center of the growth spirals indicating the screw-like dislocations (Fig. 5—8).

Though at present up-to-date, direct, big instrumental methods (such as transmissions EM, SEM etc.) are available, chemical etching is still today a general method for the study of real crystal structures.

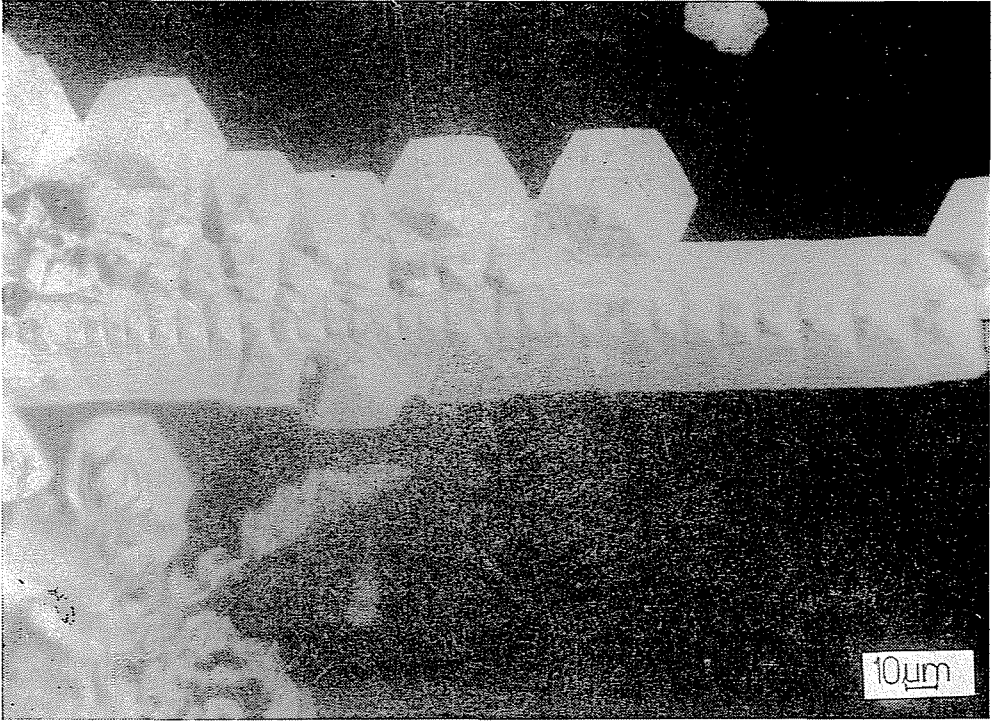


Fig. 7. Micrographs by light microscope of the etched surface of grinding grains of silicon carbide

The exact knowledge of the real crystal structures in the above described way and combined also by other methods serves also as a basis of the production technology of crystalline materials having a structure arranged from practical aspects and various purposes. Therefore, the rapid, easily performable methods of etching are still of primary importance.

### Real (Technical) Microstructures

The elucidation of the relationships between the structure and properties of heterogeneous systems consisting of phases whose building-up is complex to a degree varying from case to case and the experiences relating to the structure and investigation of crystalline substances during the design of this work are necessary requirements but the actual solution requires a view of a more complex nature.

The “strategy” of solving this problem, its main points and scheme are summarized into a system in Fig. 9.

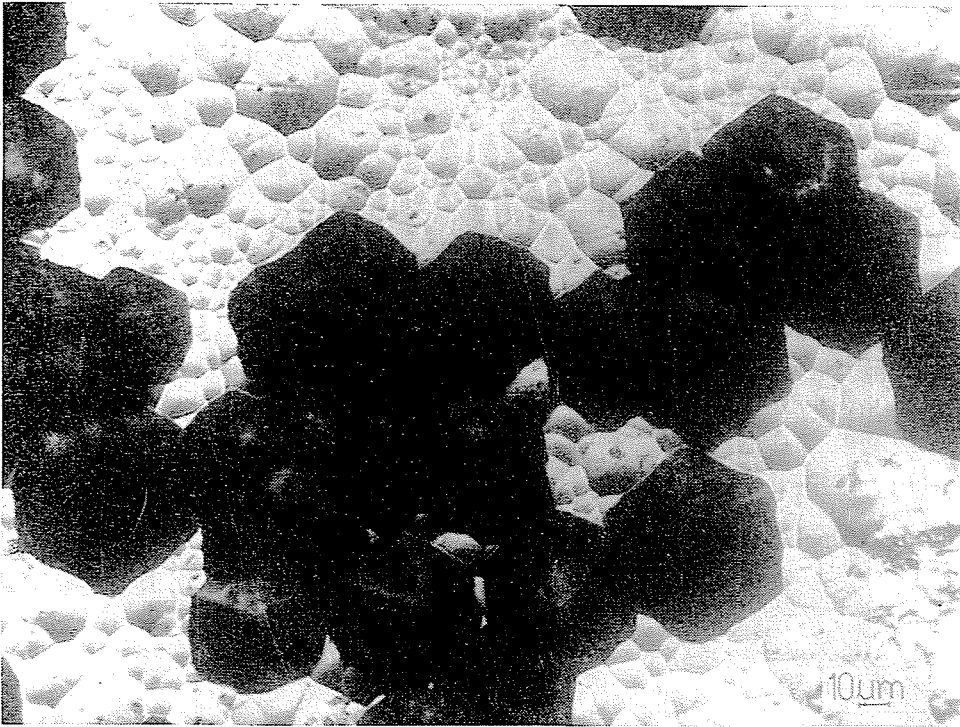


Fig. 8. Micrographs by light microscope of the etched surface of grinding grains of silicon carbide

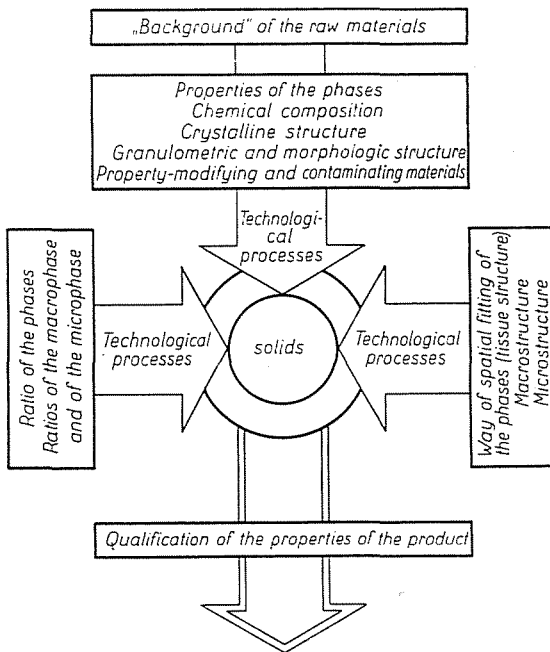
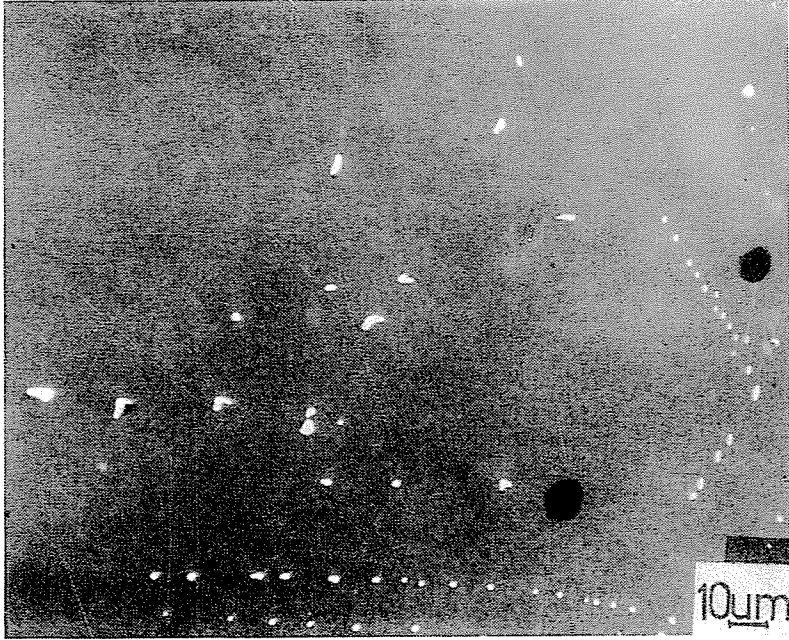
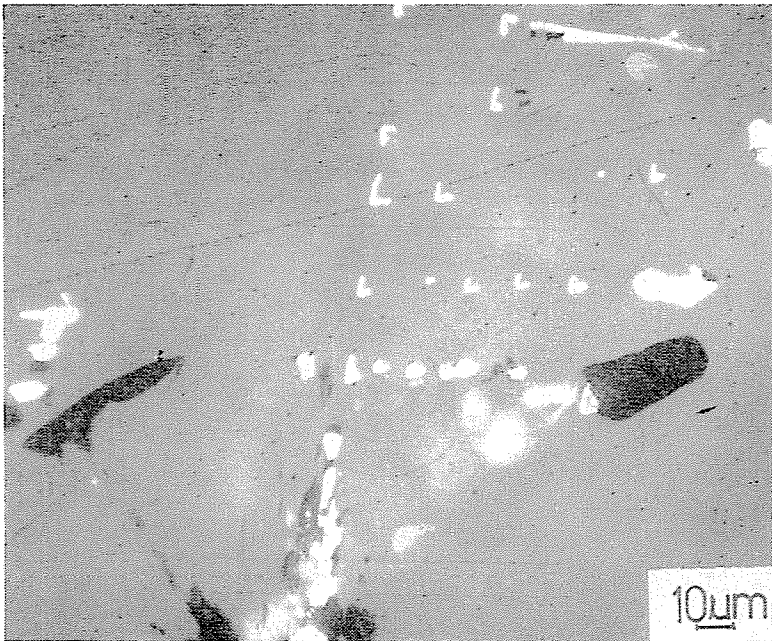


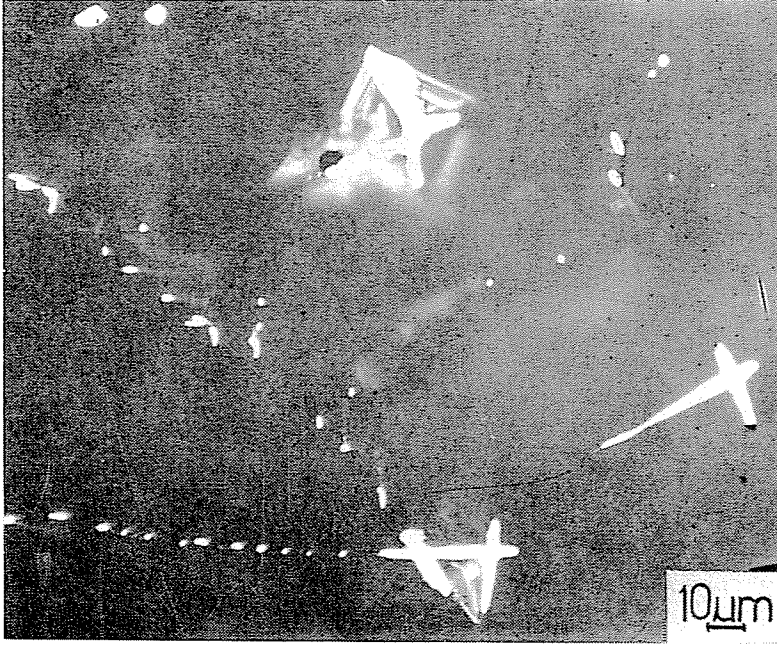
Fig. 9. Correlation of factors determining the properties of solids



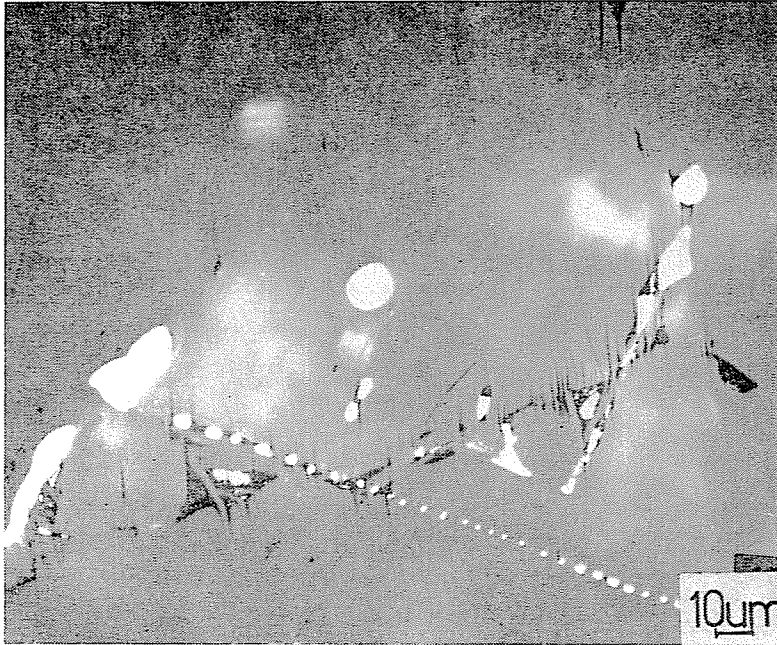
a)



b)



c)



d)

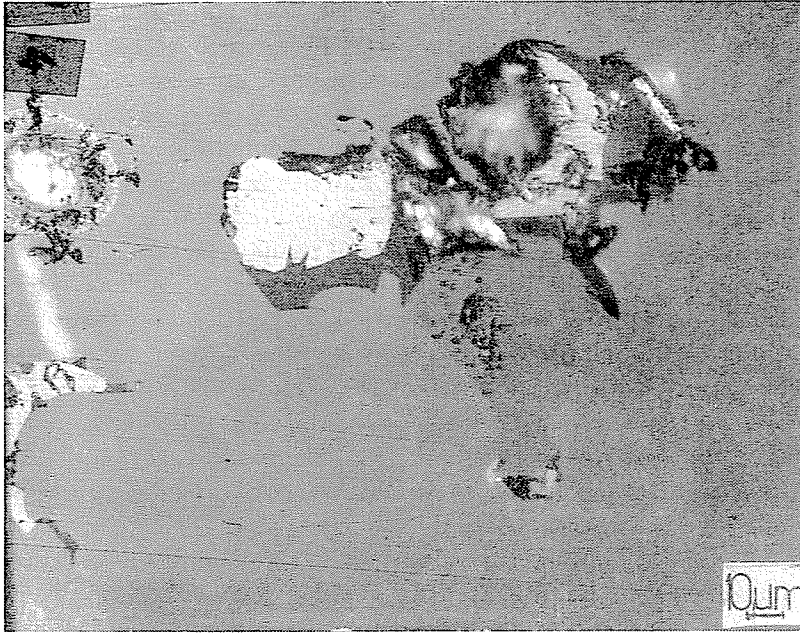
Fig. 10. Distribution of various property-modifying and contaminating substances in normal electrocorundum. Light photomicrographs



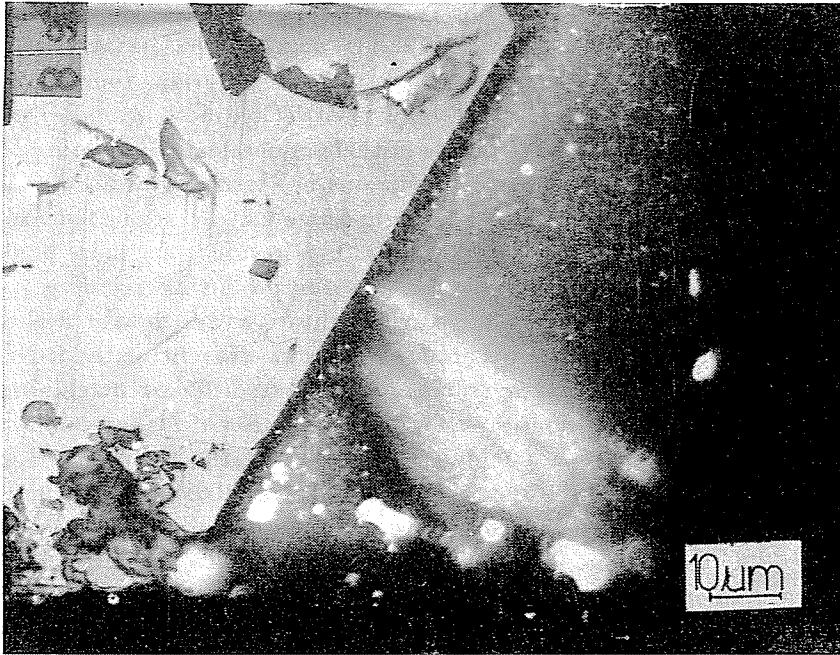
a)



b)



c)



d)

Fig. 11. Distribution of various property-modifying and contaminating substances in normal electrocorundum. Light photomicrographs

On starting at the production of given products limits, the production technology must be planned and controlled by scientific consequence, due to as a rule extremely diversified compositions and structures of these native raw materials.

A characteristic example of the materials mentioned above is the so-called normal corundum produced from bauxite by electrothermal processes (Fig. 10—11).

The extremely varying composition and tissue structure of normal corundums have been studied by investigations by optical microscope, microprobe and laser spectrography. These investigations have been prepared partly with blocks of normal corundum and partly with grains originating from factories of various countries. Thus, the different investigations illustrate not only the occurrence and frequency of the property-modifying and contaminating substances, and the varieties of composition of the individual samples but they are pointing just by presenting these characteristics to differences between the various production technologies.

In the examined normal corundum samples we found, besides aluminium, the components: Ti, Si, Ca, Mg, Zr, Hf, S, Cr, Mn, Fe, C, K, Na, V. In addition to the quality and quantity of the great number of these property-modifying components also the way of their distribution is of importance. In this respect similarly great differences can be observed between the individual samples.

We have developed a special method to decrease the deviations in abrasive machining due to the heterogeneous structure of grains (our application for the relevant patent has already been filed). This method makes possible the fractionation of grains on the basis of their mineralogical structure leading to the result that the properties of the grains are virtually uniform, and respectively, the grains having different properties can be separated into well defined quality groups (different fractions). This result is the more important because the possibilities known up till now for producing grinding tools of adequate quality (by the quantitative and qualitative variations of the bonding material) have been increased by an entirely new, efficient method. Namely, grain-fractions of nominally the same quality but different machining efficiency may serve as initial materials for the production of higher quality tools.

The different abrasive machining properties of the fractionated groups of grains were determined by the so-called *toughness* that can be measured numerically on the basis of resistance to abrasion in ball mills. Between the toughness values of the individual fractions deviation of more than 60% were measured in certain cases.

The data of the toughness tests are supported by the measured results of microhardness.

If the requirements concerning the products are stricter and the desired component is present in a raw materials must be "liberated" from the detri-



mental consequences of their "history" mostly by expensive technical operations.

At products formed by the removal of the major part of contaminating and property-modifying substances in the course of the mostly expensive but purposeful technological operations, new wide-field possibilities may arise for property improving or for novel uses. At the same time also properties not prevailing so far may or can arise, together with contaminating and property modifying substances in amounts eventually lower by several orders of magnitude.

For example the behaviour of electrocorundum manufactured from alumina is affected mainly by the contaminating component sodium aluminate:  $\text{Na}_2\text{O} \cdot 11 \text{Al}_2\text{O}_3 \text{ D}_{6h}^4 - \text{C6}$  (mmc), denoted earlier and frequently even now as  $\beta$ -corundum. This compound is detrimental when present in great amounts and particularly in case of its local enrichment because it decomposes on the effect of heat and thus reduces the strength of the grain.

Examples of those mentioned above are the extremely diversified properties of alumina and hydrated alumina produced from bauxite and the possibilities of their use in a great number of industrial branches. The series of the metastable modifications of alumina proves already that by the effect of heat, pressure and sodium hydroxide the bauxite can be practically liberated from the traces of its "history", and eventually only sodium monoxide interferes with its properties, due to imperfections of the production technology. Furthermore, mainly the possibilities of variation allowed by the crystalline structure have to be utilized.

The variability of the crystalline structure and the relationship of the properties with the polytypes of grinding grains of silicon carbide are demonstrated.

The number of polytypes of silicon carbide is great. Up to the present more than thirty polytypes have been discovered.

Table I  
More important modifications of silicon carbide

Modification	Ramsdell symbol	Stacking sequence	Number of double layers in the elementary cell	Crystal system	c/a ideal
$\beta$ -SiC	3 C	ABC ABC...	3	regular $T_d^2 - F 4 3 m$	$\sqrt{6} = 2.450$
SiC I	15 R	ABCBACABACBCABC...	15	rhomboidal $C_{3v}^5 - R 3 m$	$5 \sqrt{6} = 12.2475$
SiC II	6 H	ABCACB...	6	hexagonal $C_{6v}^4 - P 6_3 mc$	$2 \sqrt{6} = 4.899$
SiC III	4 H	ABAC...	4	hexagonal $C_{6v}^4 - P 6_3 mc$	$4/3 \sqrt{6} = 3.266$

The major part of these polytypes occur, however, only rarely. Technical silicon carbide contains only a few polytypes (Table 1). The properties of technical silicon carbide are influenced by the quantity and proportion of the various polytypes.

In the production and still more during the use of grinding tools a frequently discussed theme is the difference between the green and the black silicon carbides and how this difference affects the grinding properties.

Characteristic zones are formed in the silicon carbide furnaces during their operation. By observing these zones the changes in the conditions of crystallization along the axis of the furnace can be followed.

On the basis of the results of the investigations of grain materials produced in silicon carbide plant during longer operational periods, the following general regularities were established:

1. The silicon carbide produced by foreign factories of grinding grains consists of a mixture of three polytypes (6H, 15R and 4H). In certain charges of silicon carbide the cubic modification may also occur.
2. The polytype composition of silicon carbide shows a regular alteration along the radius of the furnace.
3. In the lode of silicon carbide the resistor core is surrounded by a zone which consists solely of the polytype 6H.
4. The monophase zone (6H) converts at first into a polyphase zone of  $\alpha$ -SiC then into another zone which contains also  $\beta$ -SiC.
5. On retreating further from the core the amount of phase 6H in the multiphase zone decreases.
6. In the multiphase zone of the form of the polytypes 6H and 15R, and the amount of 15R ranges in general from 5 to 35%.
7. In the "black" furnace the multiphase zone consists of the types 6H (15–95%), 15R (5–30%) and 4H. The amount of the latter may be as high as 70% in the vicinity of the exterior border of the zone.
8. In the "green" furnaces the phase 4H is formed only in the loose layer of small crystals occurring in the immediate vicinity of the amorphous layer. The amount of this phase is even in these parts not higher than 10%.
9. The maximum amount of phase 15R (40–65%) occurs both in the "green" and in the "black" furnaces in the lateral parts of the lodes.
10. The phase composition of silicon carbide is determined by the composition of the mixture and by the operational conditions of the furnace. The colour of the product cannot be considered as an unequivocal indicator of the polytype structure.
11. Impurities (graphite, silicon, quartz, and rock-salt in the "green" furnaces) often occur in the samples withdrawn from the outer zone.

The phase composition of various batches of silicon carbide marketed is identical with average phase composition of the furnaces, and is identical

quite independently of the grain size. Batches of green silicon carbide contain only minute amounts of type 4H, if at all, because during the comminution and selection of the lodes this type is separated and is not introduced into the commercial product.

The phase composition of the green and black silicon carbide batches leaving the plants in various periods may vary.

Of the mechanical properties, the effect of phase 4H on the fragility, hardness and grinding efficiency of the grains was investigated. It was found that the properties of the green and black silicon carbides of identical composition (i.e. consisting entirely of polytype 6H) are identical. With increasing contents of phase 4H the capability of self-sharpening connected with fragility decreases appreciably.

Despite the difficulties of measurement it can be stated that the microhardness measured on the basal plane is the highest in the case of the polytype 15R and the lowest in the case of polytype 4H.

Investigations of the capability of grinding proved similarly that grinding grains containing 80% of the polytype 4H are the worst.

A complex example is presented here in order to elucidate the role of electron structure in technical microstructures.

#### **Relationship between Electron Structure, Capability of Being Machined and Grindability**

The significance of electron structure has already been made clear when discussing the investigations of the processability of titanium and its alloys.

In the crystal of titanium metal, owing to the metallic bond, a significant part of the valency electrons are not fixed to a site. In the crystal of titanium metal, owing to the metallic bond, a significant part of the valency electrons are not fixed to a site. In contrast, the compounds of abrasive grains for machining are of a type of covalent bond. During the intensive contact in the course of abrasive machining the nonlocalized electrons of titanium are captured by the atoms of grinding grains. This manifests itself macroscopically in the sticking of metallic titanium onto the grinding grains. From this it follows that machining materials at the use of which no electron capture takes place are favourable for the abrasive grinding of titanium. From this aspect pure diamond appears to be ideal since its extraordinary hardness and other favourable technical properties are based on its crystal structure and, furthermore, can also be interpreted by its valency electrons in fixed positions. In fact, diamond is a first-class material for the abrasive machining of brittle metals of high strength. In such cases the separation of the surface layers of the very hard, brittle material to be processed occurs without any perceptible deformation, and owing to the high thermal conductivity of diamond the grind-

ing temperature does not exceed 500 °C. Thus no polymorphous modification of diamond takes place.

In the abrasive grinding of plastic metals (such as steel and titanium alloys) the separation of chip is accompanied by a plastic deformation combined with the development of a significant amount of heat resulting in the conversion of diamond to graphite. Diamond, owing to its low resistance to heat and high brittleness, is unsuitable for the abrasive machining of titanium alloys despite the favourable electron structure of diamond.

A close correlation is between the useful properties of grinding grains of high hardness and high capability for abrasive machining on the one hand, and their electron structure on the other hand. The tetrahedrally coordinated carbon atoms in diamond possess the most stable  $sp^3$  hybrid configuration. The high energetic stability of this configuration secures the localization of the valency electrons of carbon. On progressing from diamond towards silicon the energetic stability of  $sp^3$  configurations decreases and attains a minimum level in the case of lead. The high statistical value of  $sp^3$  configurations and, respectively, the corresponding rigid hybrid bonds result in the great hardness of diamond which property decreases in the case of silicon in the above discussed sense, reaching a minimum in lead. The electron configuration of cubic boron nitride (Borazon) resembles that of diamond ( $B-2s^2p^3$ ,  $N-2s^2p^3$ ), and thus its hardness and capability for abrasive machining are only slightly below those of diamond.

On the basis of what has been said above it can be understood why the hardness and the ability to use silicon carbide for abrasive machining are lower than those of diamond. Namely, the statistical ratio and energetical stability of the  $sp^3$  electron configurations of silicon atoms are also lower than those of carbon atoms. From this aspect boron carbide has more favourable properties. This may be attributed to the decrease in the principal quantum number of the  $sp$  valency electrons and, respectively, to the higher statistical ratio of the  $sp^3$  configuration. It is known that the hardness of boron carbide is essentially lower than that of diamond and of Borazon (cubic boron nitride) because the formation of the  $sp^3$  configuration is combined with electron exchange in the case of the boron atom, which results in a non-localized electron surplus. In hexagonal boron nitride the extent of this hardness decrease is still greater because during the formation of boron nitride the boron atom transfers its valency electrons to the nitrogen atom. As a result of this compound formation the electron configuration will be: ( $B-s^2p-sp^2$  and  $N-s^2p^3 + sp^2 = s^2p^6$ ). Besides the appearance of the less stable  $s^2$  configuration the appreciably asymmetric distribution of electron density in the lattice leads to hardness decrease.

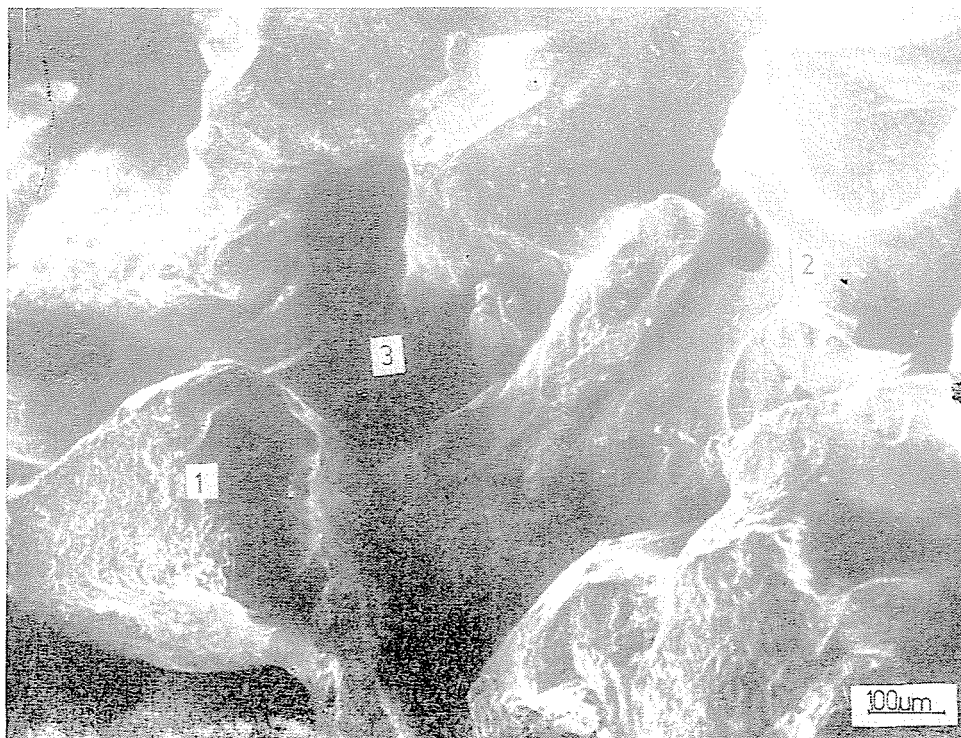
On investigating the general fundamental problems of the development of grinding tool production and of grinding operations, it becomes obvious that

the real basis of modernization is the recognition and utilization of the fundamental relationship between microstructure and properties.

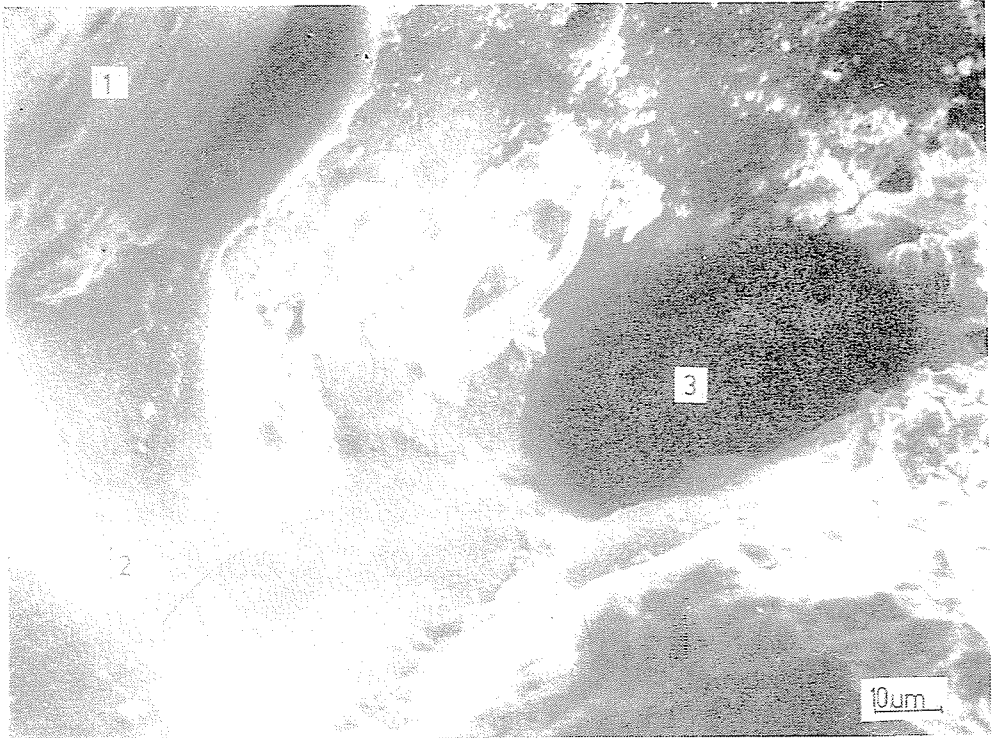
Ceramically bonded grinding tools were chosen as model substances because in their construction two forms of appearance of solids are realized, viz. the crystalline state and the amorphous vitreous state. In addition, between these components a peculiar transitional layer is formed in the course of high-temperature reactions in the solid and melt phase: furthermore, intensive interactions take place during grinding processes between grinding tools and virtually all solid materials.

### Structure of Grinding Tools

The textural structure of ceramically bonded grinding tools built up of grinding grains, bonding material and air pores is determined by the way of fitting of grinding grains coated by bonding material and coupled to each other with bonding material bridges (Figures 12 and 13).



*Fig. 12.* Micrographs by scanning electronmicroscope of the textural structure of a ceramically bonded grinding tool of corundum grains. 1: Electrocorundum grain coated by bonding material, 2: Bonding material bridge, 3: air pore



*Fig. 13.* Micrographs by scanning electronmicroscope of the textural structure of a ceramically bonded grinding tool of corundum grains. 1: Electrocorundum grain coated by bonding material, 2: Bonding material bridge, 3: air pore

The bonding material bridges of grinding tools from electrocorundum grains have in ideal cases a hyperboloidal shape. In practice, this shape deviates from hyperboloidal more or less.

The development of the various tissue-texture types of grinding tools from electrocorundum grains and their peculiarities can be studied on glass spheres of a size corresponding to that of the most frequently used grinding grains as model substances which spheres are bonded by readily melting bonding materials (Fig. 14).

On increasing the amount of bonding material from 2 to 30% the development of three different types of tissue texture shown in Figures 15 and 16 can be observed.

In case of bonding material contents of 2–8%, the coat of bonding material is hardly observable by the light microscope. The major part of bonding material is consumed by the formation of a bonding material bridge between the glass spheres. The minimum content of bonding material required in grinding tools produced in practice is about 8%.

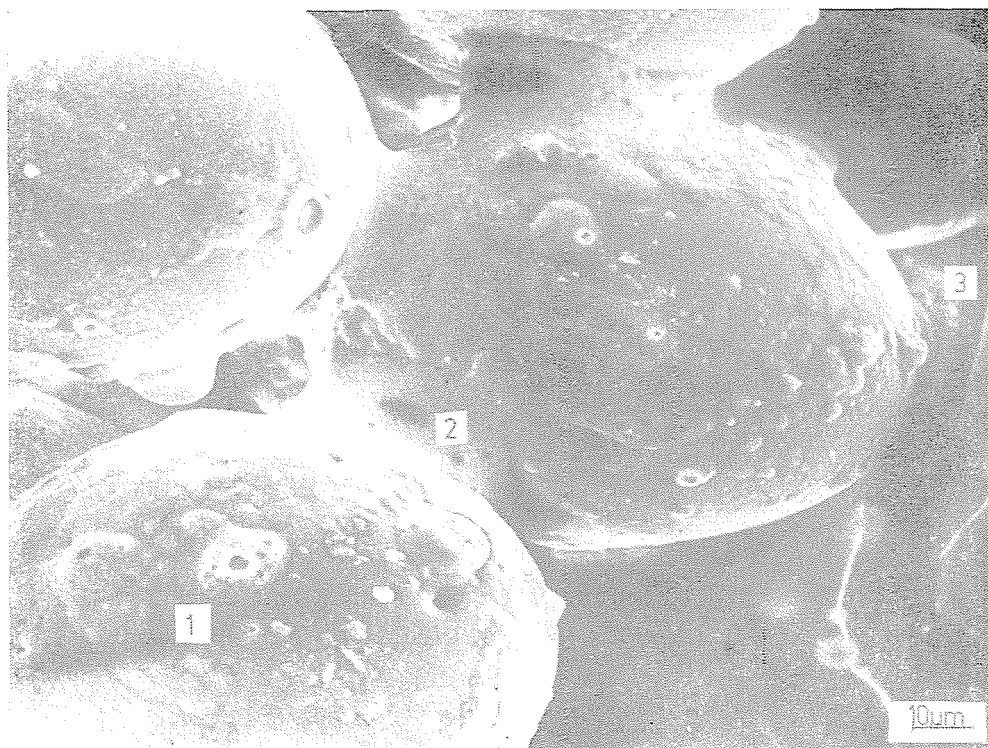


Fig. 14. Development of types of structure as a function of the amount of bonding material. (1: Glass sphere, 2: Bonding material bridge). Scanning electronmicrograph

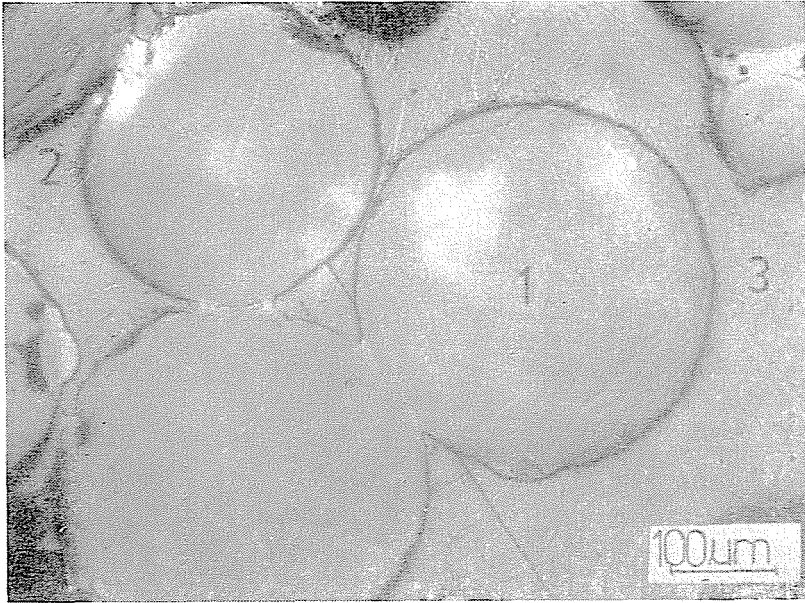
On increasing the amount of bonding material from 10 to 28%, the dimension of bridges rises gradually at the simultaneous thickening of the bonding material coat. The above given amount of bonding material corresponds with the proportion of bonding material applied in practice.

A bonding material content of over 28% interferes already with the regular structure. The appreciable thickening of the bonding material bridges is accompanied by partial deformation, by an increase of the distance between the glass spheres and by their embedding into the bonding material.

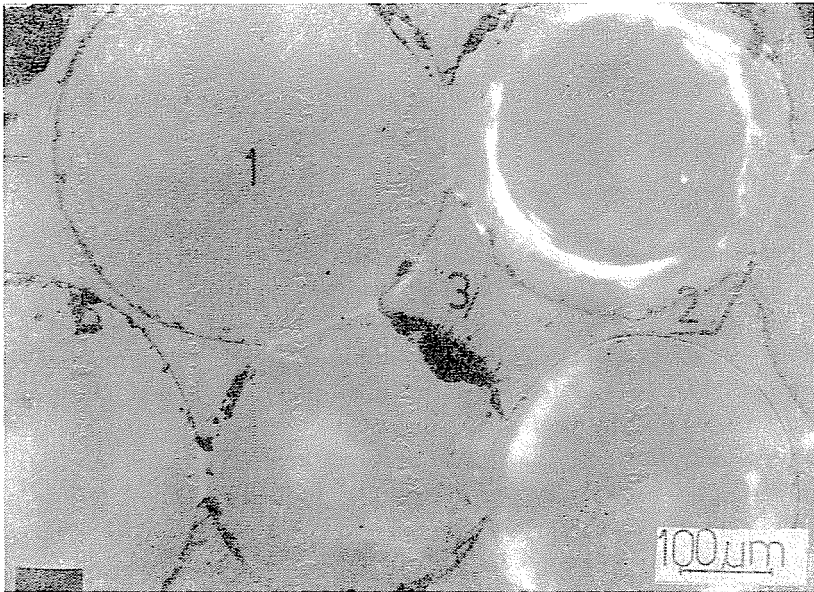
The development of the tissue texture furnishes valuable informations for the design of the quality degrees of ceramically bonded grinding tools.

In the course of the production (firing) of ceramically bonded grinding tools, a transitional phase of a composition and properties differing from those of the electrocorundum grains and of the bonding material is formed at the phase boundary of these two components.

The transitional or bonding layer formed during the firing of grinding tools (which is of an order of magnitude of 10  $\mu\text{m}$  in the majority of cases),

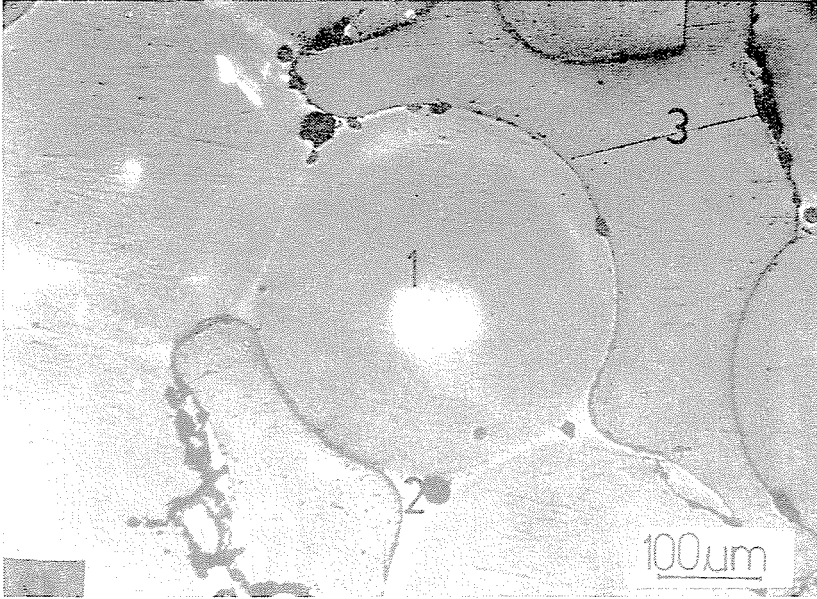


a)



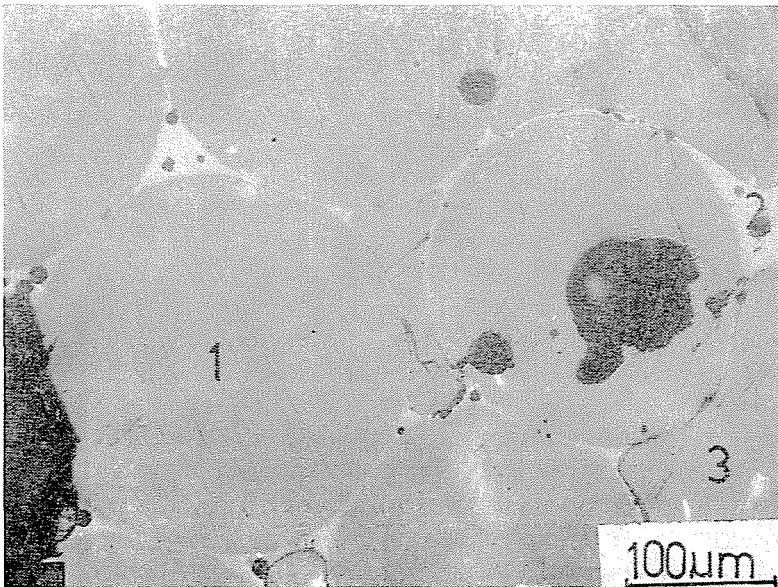
b)



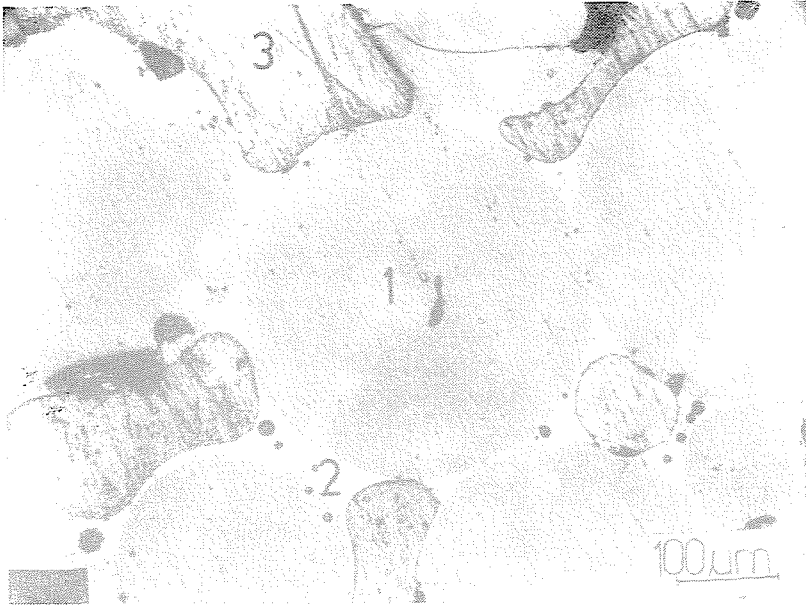


c)

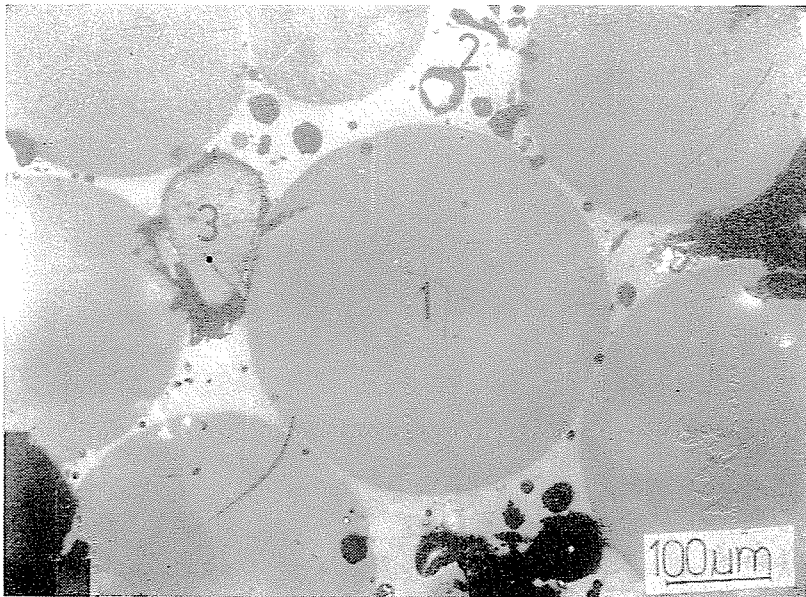
*Fig. 15.* Development of types of structure as a function of the amount of bonding material. (1: Glass sphere, 2: Bonding material bridge, 3: Embedding resin.) Light photomicrographs. a: 2%, b: 6%, c: 12%



a)



b)



c)

**Fig. 16.** Development of types of structure as a function of the amount of bonding material. (1: Glass sphere. 2: Bonding material bridge, 3: Embedding resin.) Light photomicrographs. a: 16%, b: 28%, c: 30%

also behaves in a different way from a light-optical aspect, due to physico-chemical processes taking place between the bonding material and the grains of electrocorundum. At the boundary of grains in a sample of electrocorundum—bonding material investigated for purposes of demonstration and presented here by photomicrographs, a zone still adhering to the grain but having a microstructure differing from that of the grain can be seen (Fig. 17). The

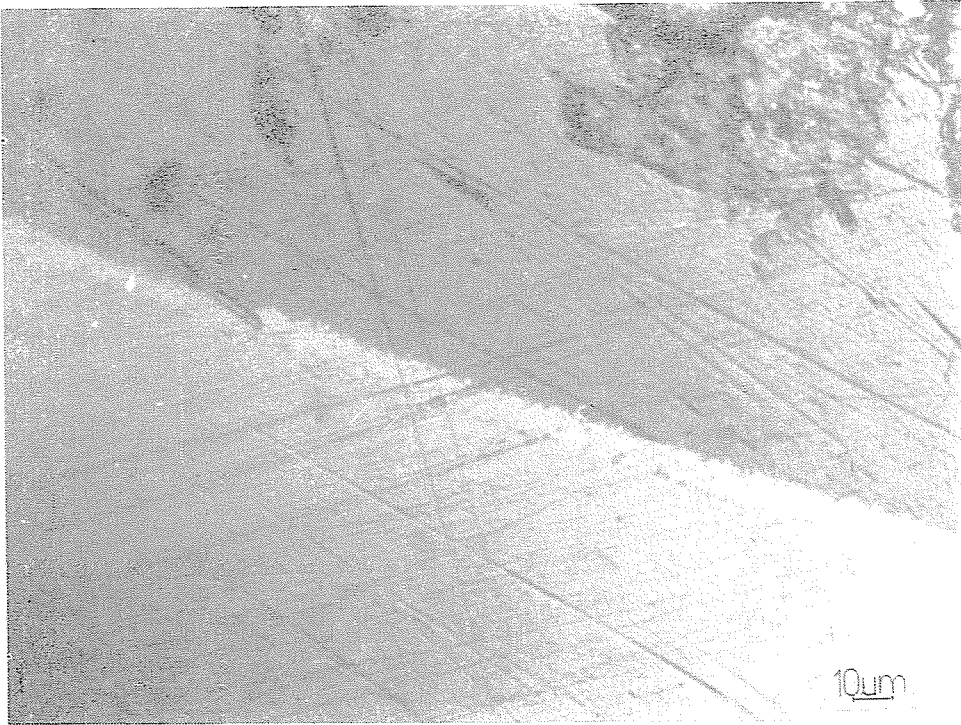


Fig. 17. The environment of the phase boundary of electrocorundum (1) and ceramic bonding material (2). Light photomicrograph

boundary line of this layer facing the bonding material (Fig. 18) is of an articulated nature instead of a continuous connection. During firing processes carried out at high temperature, corundum grains are decomposed vigorously by bonding materials of such an extremely high reactivity.

However, such materials are used in practice only rarely, though they reflect the process in an exaggerated but descriptive way. In such cases the microcrystals and corundum particles loosened at the phase boundary of corundum grains “swim off” to various distances from the electrocorundum grain during the period of peak temperature, the length of distances depending

on the viscosity of the melted bonding material (Fig. 19). The corundum particles separated from the electrocorundum grinding grains and which migrate into the melted bonding material are decomposed there.

In the case of up-to-date bonding materials used in industry, and under controlled firing conditions, the partial decomposition of the surface of corundum grains and the formation of the bond take place in a way more gradual than in the cases discussed above, and they are not accompanied by a process

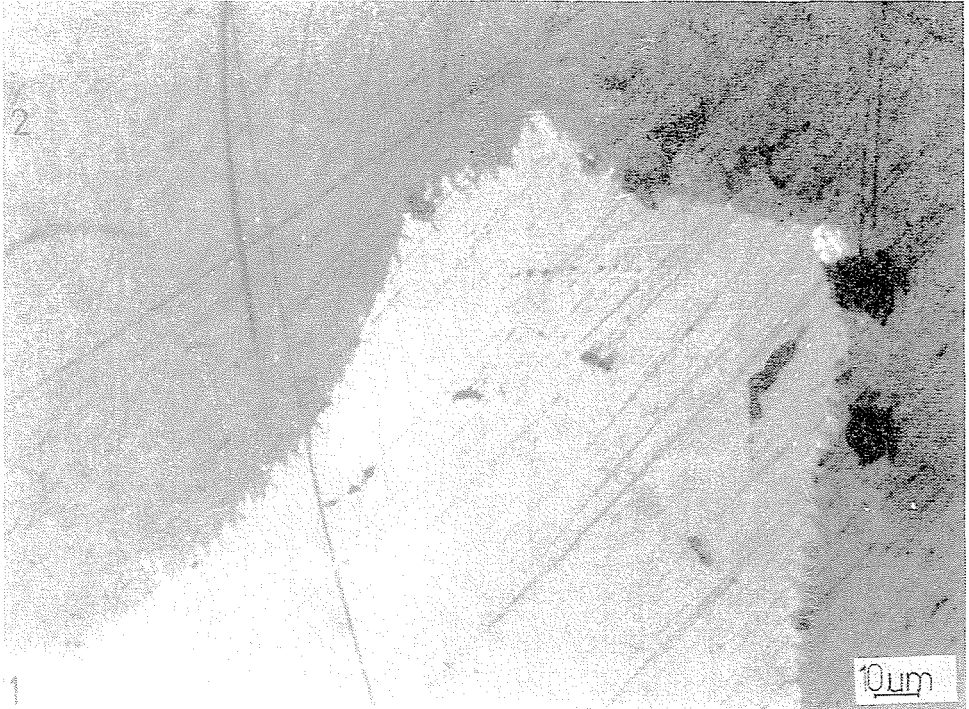
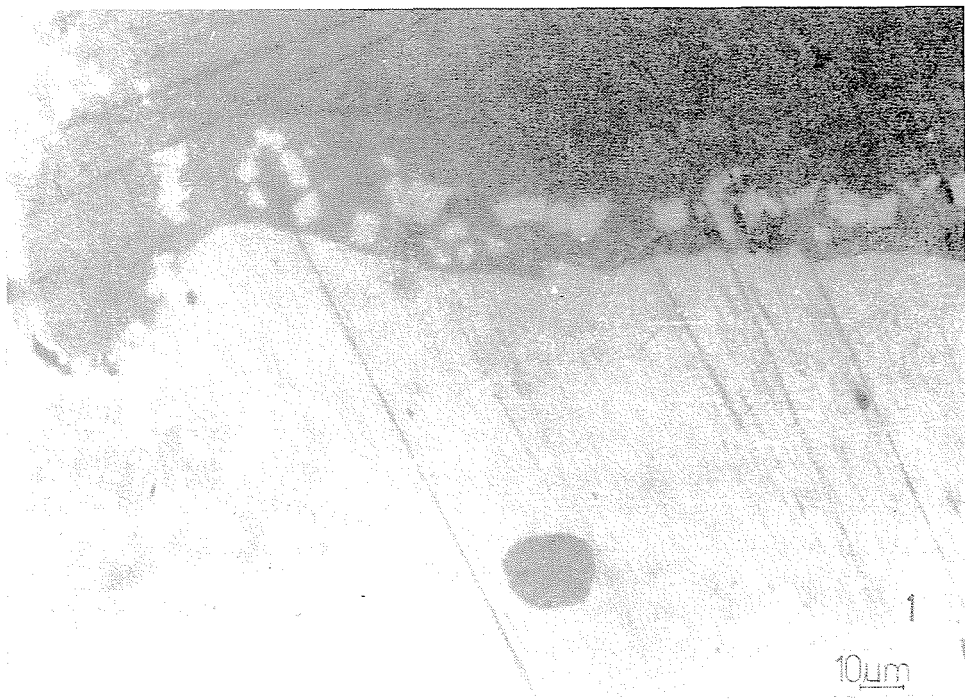


Fig. 18. The environment of the phase boundary of electrocorundum (1) and ceramic bonding material (2). Light photomicrograph

which consists of a vigorous or exaggerated loosening of the corundum surface and by a migration of the loosened, larger particles. On the effect of the decomposition process the alumina content of the bonding material increases in both cases to an extent that the softening point and deformation temperature of the bonding material rise by several hundred degrees. This explains, for example, why grinding tools can be fired even at about 1300° C without the hazard of deformation in the presence of a bonding material which when heated alone already becomes soft at a temperature of about 1100 °C.

At the fracture of the grinding tool samples we investigated with scanning electron microscope, the structure of the grinding grain and of the bonding

phase, and their mode of coupling appear individually in a very plastic form. The breaking properties of the bonding layer (which becomes wider with the increase of the firing period of grinding tools) differ visibly from the behaviour of both "pure phases". The "socket" having a different structure and different properties also influences the way of breaking (fracture) of the grinding



*Fig. 19.* The environment of the phase boundary of electrocorundum (1) and ceramic bonding material (2). Light photomicrograph

grains due to mechanical effects, and thus it may modify or control the self-sharpening of grinding tools (Figs 20–21).

This phase is the actual bonding layer whose properties can be controlled in a very sensitive way by the quality of components which react each other during firing and by the firing technique (see Figs 22–24).

The microstructure of the transition layer and its environment furthermore within this the observable characteristic details reflect, just as the sea in a small drop, the result of the interactions taking place between the components which result represents also the level of the conscious application of the relationships shown in Fig. 9.

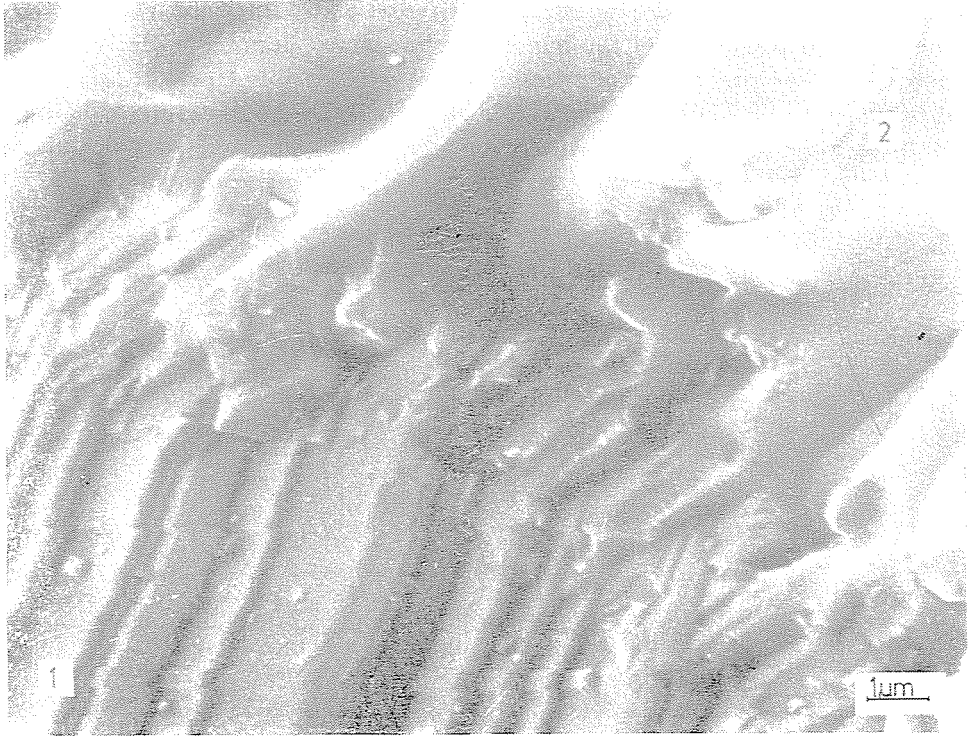


Fig. 20. Scanning electronmicrograph of the phase boundary between electrocorundum (1) and ceramic bonding material melt (2)

### Present and Future Research Program of the Ideal and Real Microstructure Systems

- I. Microstructure systems of first grade  
(From the fundamentals known up to the present to the crystalline arrangement, inclusive).
- II. Technical microstructure systems  
(Demonstrated by various series of technical model substances in which the system of first grade come more or less in the foreground).
- III. Ideal microstructure systems  
(A system documented, developed on theoretical basis and proved by very great number of figures related to each other).
- IV. Theoretical and practical proof and synthesis of the unity of the research systems I, II and III  
(Both the presented lecture and some enlarged details of the ideal and real microstructure system have been summarized in the work given in the references).



*Fig. 21.* Scanning electronmicrograph of the phase boundary between electrocorundum (1) and ceramic bonding material melt (2)



Fig. 22. Electron microscope image of the phase boundary between electrocorundum (1) and ceramic bonding material melt (2)





*Fig. 23.* Electron microscope image of the phase boundary between electrocorundum (1) and ceramic bonding material melt (2)

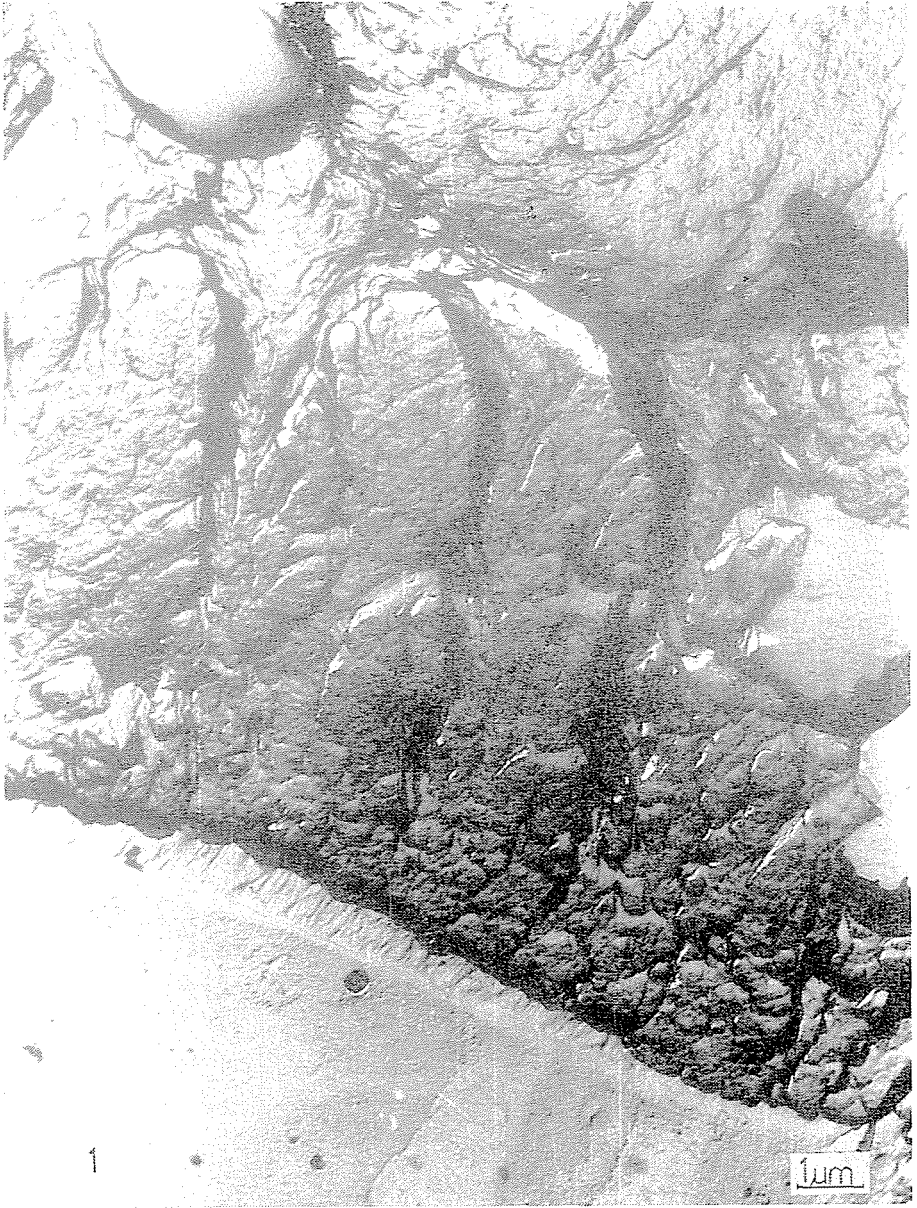


Fig. 24. Electron microscope image of the phase boundary between electrocorundum (1) and ceramic bonding material melt (2)

## Summary

On investigating the general fundamental problems of the development of grinding tool production and of grinding operations, it becomes obvious that the real basis of modernization is the recognition and utilization of the fundamental relationship between microstructure and properties.

With this aim in view we have chosen as the leading idea of our work the elucidation and outlining of the theoretical, technical and technological relationships of ideal microstructures and of real microstructures.

The essence of this idea is that microstructures must be understood both from mathematical and structural viewpoints because microstructures are constricted in a geometrical way.

Ceramically bonded grinding tools were chosen as model substances because in their construction two forms of appearance of solids are realized, viz. the crystalline state and the amorphous vitreous state. In addition, between these components a peculiar transitional layer is formed in the course of high-temperature reactions in the solid and melt phase; furthermore, intensive interactions take place during grinding processes between grinding tools and virtually all solid materials.

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