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# Additives for Abrasive Materials

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Additional information is available at the end of the chapter

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## Abstract

The overarching objective of the chapter is to acquaint the readers with the topic associated with the production of abrasive tools and presentation of the most significant research results regarding the determination of the most important functional properties of selected additives (described in the literature and established on the basis of authors' own scientific experiences). The studies regarding various additives, which were characterized in detail in the literature, were mainly based on thorough physicochemical and microstructural analysis as well as the determination of basic strength and thermomechanic parameters. The attempt to implement alternative cross-linking agents, which would result in the limited release of volatile organic compounds, is also of great importance in terms of production of environmentally friendly final products. A subsequent aim is to attract the attention of a wide range of readers and popularize the topic associated with conventional abrasive materials and next-generation abrasive compositions.

**Keywords:** abrasive machining, abrasive tools, binders, functional fillers, biopolymers

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## 1. Introduction

Modern abrasive tools used in industry are required to fulfill a number of conditions relating to quality, durability and performance. Progress in a wide range of areas related to materials engineering has made it possible to use abrasive machining in place of complex specialized processes. Recent work on the development of abrasive tools has been focused on the search for functional additives, above all to improve the functional properties of the product through the addition of fillers that primarily increase adhesion between the grains and binder. Another key issue is to obtain more environmentally friendly final products by reducing the quantities

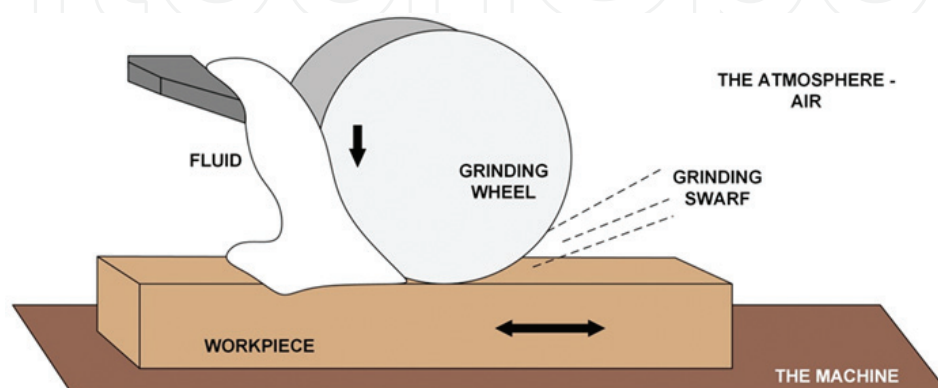
of harmful compounds released, which can be done by using alternative cross-linking agents. In this chapter, the authors focus above all on the aforementioned questions, describing both the current state of knowledge and likely directions of future development in these areas.

## 2. The basics of abrasive machining

Abrasive machining is the most popular method of finishing, in which an abrasive tool (usually in the form of a grinding wheel or disk) rotating at high speed is used to remove the surface layer of a softer material. In modern industry, grinding technology is constantly being developed, in line with specific requirements applicable to a wide range of products and processes. Grinding is a key stage in the technology of production for advanced products and surface treatment in many fields of industry. The technique has many advantages over other surfacing methods.

A grinding process can be used for precise operations in the production of high-quality parts, with high accuracy and small dimensional tolerance [1]. It can be used to produce both very large machine parts and small objects such as optical instruments, elements of electronic devices, silicon wafers and rolling bearings. Another invaluable feature is the possibility of adjusting the abrasive machining process to remove large quantities of material in a short time. High grinding performance is necessary when it is required to remove a significant quantity of the machined material in a single fast operation. This applies, for example, in the cleaning of castings in foundries. Abrasive machining is also a technique used in working with very hard materials and hardened surfaces. In many cases, it is the only feasible method of finishing the surface of hard materials. The increasingly popular use of inorganic materials composed of ceramics and hard minerals with a crystalline structure enables the elimination of problems related to the finishing of surface layers. Such operations are applied, for instance, in the aerospace industry.

**Figure 1** shows the grinding process in diagram form. Six basic elements may be identified: the grinding wheel, the worked material, the coolant or cutting fluid, the machine tool, the surroundings (air) and material chips.



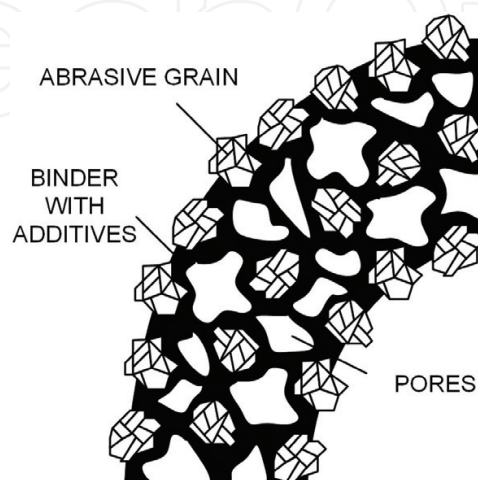
**Figure 1.** Simplified diagram of the grinding process, adapted from [2].

The most important elements playing a role in the process are the abrasive tool and the processed material. It is their properties that have a decisive impact on the course and effect of abrasive machining. Parameters of the grinding wheel, such the grain size and type, hardness, rigidity, and physical and chemical properties, determine its suitability for the machining of a given material. The choice of an appropriate tool is also dependent on the shape, hardness and physicochemical properties of the worked surface, and it is therefore essential to perform a full analysis of the material being processed [2, 3]. The process is also influenced by chemical factors. Atmospheric oxygen and high temperature favor the formation of oxides on the metal surface, which improves lubrication. Often, however, a coolant or cutting fluid is additionally used; this draws excess heat from the worked material and the tool, as well as reducing friction and extending the lifetime of the grinding wheel. Because of the greater stability of a cooled process, its accuracy can be improved and heat damage can be prevented. The technical condition of the machine tool is also important. Its purpose is to provide static and dynamic restriction of displacements between the tool and the worked object. The high quality and stability of the machine tool are therefore of key importance for achieving the desired tolerance in terms of geometry, dimensions and roughness. Unwanted vibrations of the machine may cause cracking and accelerated wear of the abrasive grains [4].

### 3. Abrasive tools

An abrasive tool is a composite material in which the continuous phase (matrix) consists of a binder, while the dispersed phase is an abrasive grain. Apart from these two basic components, additives are used in the form of fillers—active and inactive—which serve either to improve the technical parameters (active fillers) or to reduce the production cost of the tool (inactive fillers). A diagram of the structure of an abrasive tool is shown in **Figure 2**.

The industrial process of production of abrasive tools with an organic binder comprises three principal stages: mixing of components, molding, and firing (annealing) to provide cross-linking of the binder [5, 6].



**Figure 2.** Simplified diagram of the structure of an abrasive tool, adapted from [2].

The mixing of the components of the tool begins with covering of the surface of the grains with liquid resin or a solvent (such as furfuryl alcohol). The uniformly moistened grains are then mixed with powdered resin, with the addition of fillers. The resulting mixture is sieved to remove lumps or agglomerates. The mixing of the components is a very important process: too loose a consistency may cause inhomogeneity of the final product, while excessive wetness will lead to difficulties in further processing.

The next important stage of the preparation of abrasive materials is molding, which may be hot or cold. Cold molding is applied in the case of tools in which pores account for at least 10% of the volume, and the pressing time does not usually exceed 1 min. Hot molding is used in the production of non-porous grinding wheels of high density. In this case, the pressing time is longer, between 20 and 60 min, and the temperature may be as high as 150°C.

The final process is the firing of the molded prefabricated elements. This is done in industrial furnaces, according to a strictly defined temperature program. The length of the program depends on the size of the tool—with larger tools, the increase in temperature should be slower and the duration of the program as a whole should be longer. In most cases, the cross-linking process lasts between 18 and 35 h, and the temperature does not exceed 200°C (or usually 180°C).

#### 4. Abrasive materials

Abrasives are natural or synthetic materials which are used in a highly fragmented state (usually in the form of grains) as a basic component for the production of abrasive tools. Synthetic abrasive materials may be obtained by:

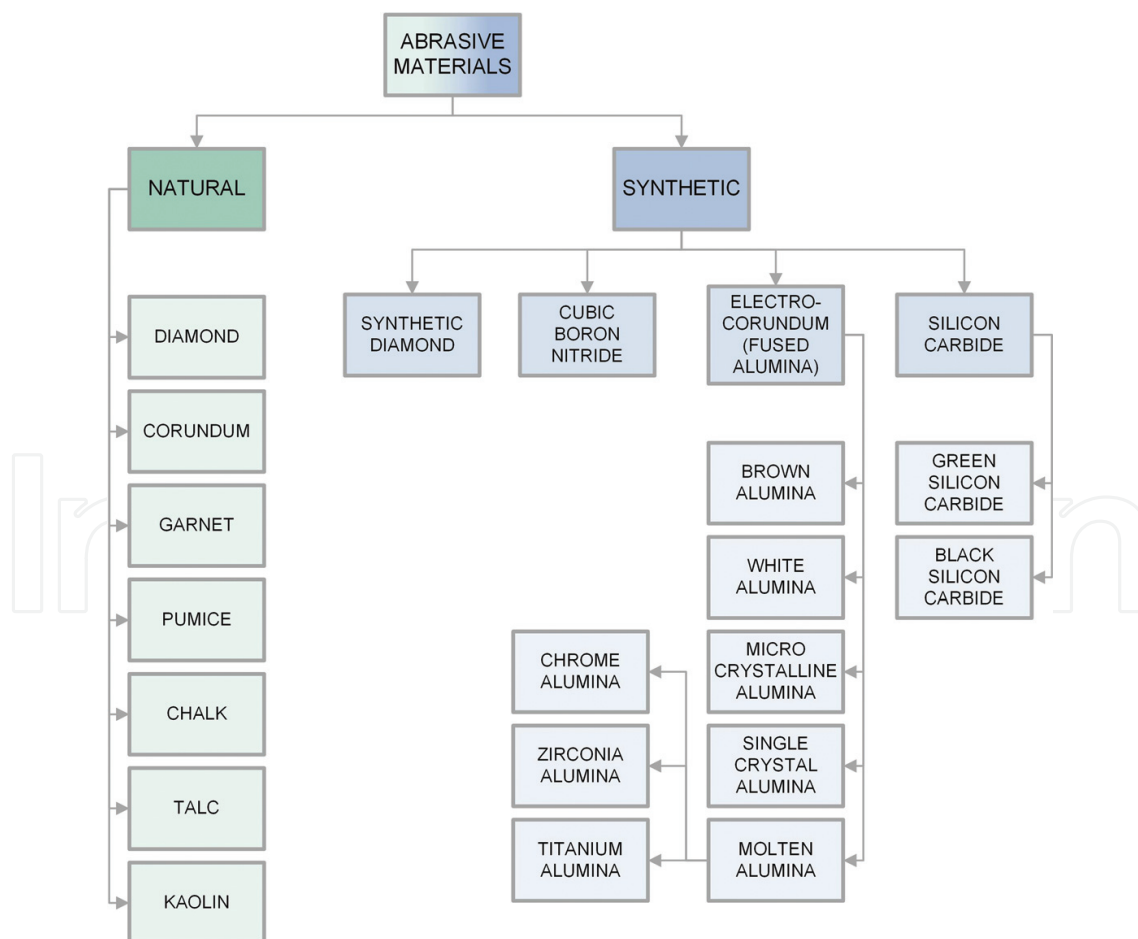
- electrothermal melting processes (synthetic corundums);
- in-furnace processes between solid and gas phases (silicon carbide);
- high-pressure processes (superhard materials such as synthetic diamond and cubic boron nitride);
- sintering processes (sintered corundums).

For a material to serve as an abrasive, at least one basic condition must be fulfilled. If a layer of material is to be removed by abrasion, the ratio of the hardness of the abrasive  $H_s$  to the hardness of the worked material  $H_m$  must exceed a certain minimum value. In the great majority of cases the  $H_s/H_m$  ratio is in the range 1.5–2.0. The hardness parameter is therefore the principal criterion determining whether or not a material can be classed as an abrasive. Another very important parameter is the material's melting point. Even in the early 1960s it was shown that during the grinding of metals the temperature may rise high enough to cause the metals to melt. This implies that abrasive materials should not have melting points below 1600°C. Due to this criterion, all known organic substances and almost 99% of inorganic substances are excluded from use as abrasive grains. A further surprising fact is that there is no known hard material containing more than four atoms. The most commonly used abrasives

are boron carbide, silicon carbide, synthetic corundums (standard, noble and modified), diamond (mainly synthetic) and cubic boron nitride. A classification scheme for natural and synthetic abrasive materials is shown in **Figure 3**.

#### 4.1. Silicon carbide

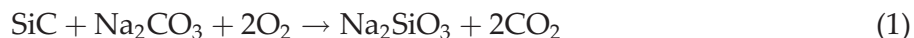
Silicon carbide, also known as carborundum, is a compound of carbon and silicon with the condensed formula SiC, composed of 70.045% silicon and 29.955% carbon. It was the first abrasive material to be obtained by synthesis. The compound was discovered by the Cowles brothers in 1885, when they were attempting to melt quartz in an electric arc between carbon electrodes. It was first produced industrially in 1891 in the United States, by the Carborundum Company founded by Edward G. Acheson, who was officially recognized as the originator of the method of production of SiC. Silicon carbide may crystallize either in a hexagonal arrangement ( $\alpha$ -SiC) or in a cubic arrangement ( $\beta$ -SiC) [7]. The atoms in the SiC crystal lattice form two interpenetrating tetrahedral structures. SiC is resistant to the action of molten metals such as Al, Cu, Pb, Sn, Zn, Cd, although it is sensitive to Fe, Ni, Cr, Co, Mn, since these metals are capable of forming alloys with SiC. It is not damaged by acidic slags or salts, although damage



**Figure 3.** Classification scheme for natural and synthetic abrasive materials, based on [4].



is caused by molten alkaline compounds, including certain hydroxides and salts. Sample reactions with such compounds are given below in Eqs. (1) and (2):



At high temperatures, SiC is able to react with certain oxides (above 800°C), including CuO and PbO, and with oxides of magnesium and calcium (above 1000°C). Up to 900°C, its stability is not significantly affected by oxygen, but above that temperature, the surface is fairly strongly oxidized. The products of this reaction may be compounds such as CO, CO<sub>2</sub>, SiO and SiO<sub>2</sub>. The role of oxidizing agent may also be played by steam or carbon(II) oxide [8].

Silicon carbide has found many applications in various branches of industry. Because of its high mechanical strength, hardness, and ability to form relatively thick crystals, it is used chiefly as an abrasive material in abrasive tools. Somewhat less frequently, it is also used to produce fire-resistant materials such as retorts, crucibles, furnace linings, bricks, and pipes in heating systems. This is possible because of its very high thermal conductivity, resistance to sudden temperature changes, and high decomposition temperature. Silicon carbide also offers high electrical conductivity, and can thus be used in electrical engineering to produce heating elements, resistors, diodes and transistors [8, 9].

#### 4.2. Synthetic corundum

Synthetic corundum is a material whose principal component is crystalline  $\alpha\text{-Al}_2\text{O}_3$  (corundum). It also contains other compounds, chiefly oxides of silicon, titanium, iron, calcium and magnesium. It can be produced in a Higgins electric arc furnace. The main raw material used to obtain ordinary synthetic corundum is bauxite. Synthetic corundum is highly resistant to the action of practically all acids and bases, both organic and inorganic. Only at high temperatures (above 900°C) does it react with molten salts of alkaline metals, producing aluminosilicates. Hydrogen causes the reduction of corundum to suboxides of aluminum, although this occurs only above 1400°C. Carbon in large excess is able to reduce  $\text{Al}_2\text{O}_3$  at temperatures above 2000°C [10].

Synthetic corundum is used practically exclusively for the manufacture of abrasive tools. Its abrasive ability is largely dependent on the quantity of additives. Apart from standard synthetic corundum, which is produced in the largest quantities, there are also other varieties, such as [11]:

- White alumina—this material contains significantly fewer impurities than standard synthetic corundum. It is generally laid down that noble synthetic corundum should not contain less than 98.5% aluminum oxide. The principal feature of this material is the possibility of self-sharpening of the abrasive grains during operation of the tool. Synthetic corundum grains have slightly lower mechanical strength, and so when the cutting edge of the crystal becomes blunted it is chipped off the tool, thus uncovering fresh, unblunted layers. This property is particularly desirable when very accurate working is required and when the tool is to apply a low pressure on the worked material.

- Modified synthetic corundums—these are materials based on aluminum oxide, produced with the addition of compounds that are able to become incorporated into the corundum crystal lattice and form solid solutions with it. The parameters of the final product can be controlled by varying the quantity and type of modifier used. The most commonly encountered modifiers are:
  - chromium oxide ( $\text{Cr}_2\text{O}_3$ )—this modifier is used to produce pink alumina, a material that has a greater quantity of crystals than white alumina, better abrasive ability, unchanged microhardness, but slightly lower mechanical strength;
  - titania ( $\text{Ti}_2\text{O}_3$ )—this modifier produces a material with high abrasive ability and greater microhardness than white alumina;
  - zirconia ( $\text{ZrO}_2$ )—this produces a material with high ductility and mechanical strength.
- Monocorundum—this is a variety of synthetic corundum with greater grain isometry and smoother faces. It has higher microhardness and mechanical strength than other varieties of synthetic corundum. Like white alumina, it has self-sharpening capacity. Because of the lower power of grinding when monocorundum is used, the worked surface heats up to a lesser degree, and this helps to prevent defects such as cracks and burn.

#### 4.3. Synthetic diamond

Diamond is one of the allotropic varieties of carbon, and is unquestionably the hardest mineral occurring on Earth (with a hardness of 10 on the Mohs scale). Since the quantity of mined diamond is insufficient to meet supply, leading to very high prices, it has proved necessary to develop a method for synthesizing diamond. This was achieved for the first time by the Swedish company ASEA in 1953. Since that time, annual production of artificial diamonds has been continuously increasing.

Diamond has a density of  $3.5 \text{ g/cm}^3$ . Its crystal lattice has the form of a cube containing 18 carbon atoms [12]. All of the carbon atoms in diamond are joined by high-energy covalent bonds, which give the material its exceptional hardness. Another important property is its very good thermal conductivity, which enables heat to be removed efficiently during grinding. It also has a small thermal expansion coefficient, which reduces thermal deformation of tools with diamond grains. Another very important feature is anisotropy of hardness and grindability. These parameters vary not only between different planes, but also depending on the direction in which the force acts in a given plane. The material is resistant to the action of very strong acids and their mixtures, but dissolves in molten hydroxides and salts such as  $\text{NaNO}_3$  and  $\text{KNO}_3$ . It also dissolves in molten iron and its alloys above a temperature of approximately  $800^\circ\text{C}$ . In the presence of air it combusts at a temperature from  $850$  to  $1000^\circ\text{C}$ . Synthetic diamonds also have several features that distinguish them from natural diamonds. They are usually smaller (with an average size between  $0.2$  and  $0.4 \text{ mm}$ ) and have different grain shapes and a rougher surface. Surface roughness, and crystal vertices with smaller angles and smaller radii of curvature are desirable features for abrasive machining. Since the content of impurities in synthetic diamonds is higher than in natural diamonds, parameters such as



mechanical strength and brittleness are somewhat inferior. Processes for synthesizing diamond are carried out at high pressures (reaching 10 GPa) and high temperatures (up to 3000°C) [13, 14].

Because of its properties, diamond is used successfully for the machining of cemented carbides and ceramic sinters, for cutting glass panels, for the working of optical glass, and for making measurements of hardness and smoothness of surfaces.

#### 4.4. Boron nitride

Cubic boron nitride (borazon) is, like diamond, a member of the group of superhard abrasive materials. Due to the similarity of the hexagonal form of boron nitride ( $\alpha$ -BN) to the structure of graphite, it was predicted by analogy that the compound must also exist in a diamond-like form ( $\beta$ -BN). This was proved in 1957 by Robert H. Wentorf, who became the first to successfully synthesize cubic boron nitride [15]. Its crystal lattice has a similar structure to diamond. Of the 18 atoms contained in a cube, four are boron atoms and the remainder nitrogen. Unlike diamond, in which all bonds are covalent, in cubic boron nitride 75% are covalent bonds and 25% ionic. This fact is significant for the mechanical properties of Borazon: its hardness and mechanical strength are lower than those of diamond. The material is exceptionally thermally stable in atmospheric air (up to 2000°C at normal pressure), being transformed back to the hexagonal form only above 2500°C. However, it is sensitive to the action of water, which at high temperature causes its decomposition into boric acid ( $H_3BO_3$ ) and ammonia. This needs to be taken into account when selecting a filler whose decomposition products include  $H_2O$ . Synthesis of  $\beta$ -BN is carried out in the presence of catalysts (such as metallic potassium) at pressures of 6.5–9.0 GPa and temperatures of 1500–2000°C [16, 17].

Borazon is not used for the machining of such hard and brittle materials as glass, ceramics and granite, for which the use of tools based on synthetic diamonds is recommended. Nevertheless, it offers excellent performance in the working of tool steels, as well as other metals and alloys. Tools containing  $\beta$ -BN can produce a ground surface of high quality, thanks to low grinding power and lower temperatures of abrasive machining.

#### 4.5. Modification of abrasive grains

Conventional abrasive materials that perform well in typical abrasive machining may prove insufficiently effective in a chemically aggressive environment or when high temperatures and grinding pressures are used. To improve the functional properties of the abrasive grain and the tools based on it, one of two routes may be selected—modification of conventional abrasives to improve their functional parameters, or the development of new methods of producing superhard materials (or improvement of existing methods) with the aim of reducing costs. Conventional abrasive materials are usually subjected to thermal or thermal-chemical processing, although more and more research is being done into the surface modification of abrasive grains.

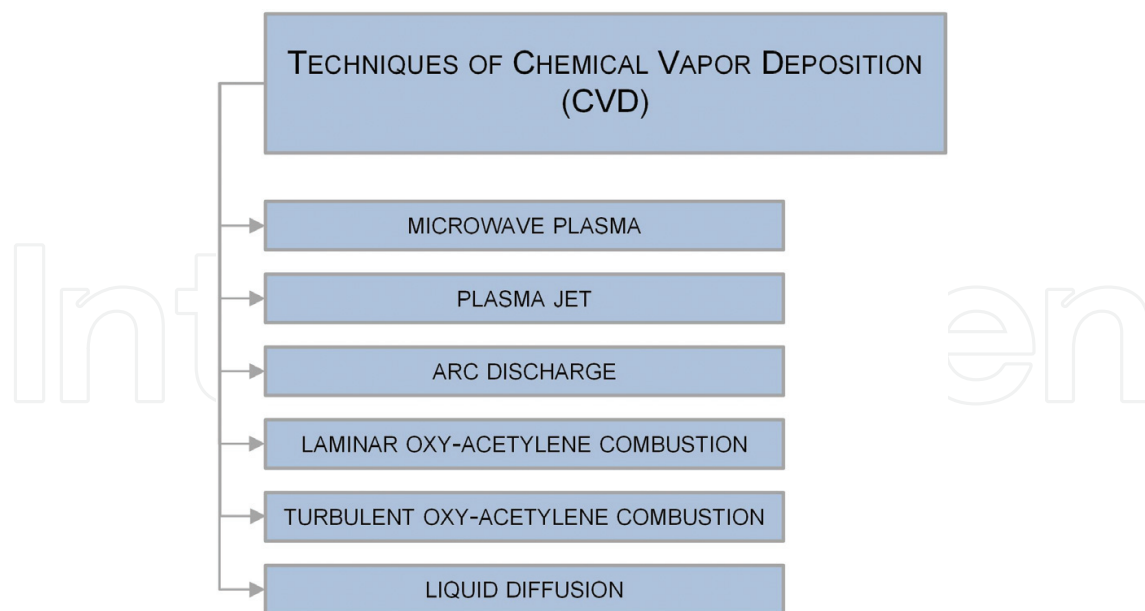
Thermal processing is among the oldest and most popular methods of modifying raw abrasive grains. It enables reduction of the brittleness of grains, particularly those of synthetic corundum, by means of roasting at temperatures up to 2000°C. This results in the creation on the grain

surface of a fine crystalline structure, which increases its operational durability and the stability of its machining properties. Roasting is carried out to eliminate undesirable impurities: sodium and potassium 11-aluminates, described as  $\beta\text{-Al}_2\text{O}_3$ . The presence of aluminates in the grain may also reduce the mechanical strength of a single grain by as much as 30%. As a result of thermal processing,  $\beta\text{-Al}_2\text{O}_3$  corundums in the form  $\text{K}_2\text{O}\cdot 11\text{Al}_2\text{O}_3$  transform completely into  $\alpha\text{-Al}_2\text{O}_3$  at a temperature of around  $1520^\circ\text{C}$ , while  $\text{Na}_2\text{O}\cdot 11\text{Al}_2\text{O}_3$  transforms at  $1700^\circ\text{C}$ . The roasting temperature may be reduced to  $1300^\circ\text{C}$  if gaseous hydrogen is used [18].

Abrasive grains are also modified to reduce the adverse impact of water-based coolants, which usually shorten the tool's lifetime. The reason for the reduced durability is the tendency of resins to crack under the influence of water, causing the grains to become loose and fall out. A way of preventing this may be to cover the grains with a layer of modifier containing hydrophilic and/or hydrophobic components. Hydrophilic components used include silanes containing amine, ureide, isocyanide, acetoxo and chloride groups. Hydrophobic silanes contain mainly phenyl, vinyl, methacrylic or epoxide groups. Surface modification using a dual-component silane-based modifier brings several undoubted benefits. The hydrophilic component covers the entire surface well, at the same time facilitating its moistening. The hydrophobic component may be applied together with the first component or as a separate layer, demonstrating the ability to bond with both the covered grains and the resin binder. Such modification prevents water-based coolants from penetrating to the interior of the tool, and thereby extends the tool lifetime, improves the material removal rate (MRR) and enhances the overall quality of the finished surface [19].

The development of innovative abrasives involves not only the modification of conventional materials but also the creation of new methods for producing superhard materials (superabrasives). The production of such materials, primarily synthetic diamond and cubic boron nitride, originally required high temperatures and very high pressures. To convert graphite to diamond, a pressure of around 13 GPa and a temperature of  $3000^\circ\text{C}$  are required. In view of the difficulty of providing such extreme conditions, other methods are used, such as solvent catalyst synthesis. This method makes it possible to reduce the high activation energy and the required pressure and temperature by a half [20]. The catalysts used in the process dissolve graphite, enabling the carbon atoms to move and to adopt the positions appropriate to diamond. Commonly used metal catalysts include nickel, iron and cobalt, as well as rhodium, palladium, platinum and others [21]. Diamond may also be obtained using non-metal catalysts, such as hydroxides and carbonate salts [22].

Of increasing importance, however, are metastable processes of diamond synthesis. An undoubted advantage of these is the relatively simple equipment required to produce diamond film and the high purity and homogeneity of the product [23]. In such processes, carbon in the form of diamond is precipitated from a mixture of hydrocarbon and hydrogen [24]. Several techniques of chemical vapor deposition (CVD) are currently applied, using microwave plasma [25], plasma jet [26], arc discharge [27] and laminar and turbulent oxy-acetylene combustion [28, 29] (see **Figure 4**). These methods require the use of high pressures and gases of relatively high purity. The gas mixture may consist of hydrogen, argon, oxygen and methane—the composition depends on the desired size of the diamond grains [30–32]. Methods have also been developed which reduce the use of harmful and expensive gases, including a



**Figure 4.** Techniques of chemical vapor deposition (CVD).

liquid diffusion method with methanol as a source of carbon, carried out in an argon atmosphere under microwave energy. This method can produce a film with a diamond content of approximately 75%, while reducing the risk associated with the use of explosive gases such as hydrogen and methane [33].

Another interesting study concerns the obtaining of single-phase nano-polycrystalline diamonds using direct conversion from graphite under high temperature and ultra-high pressure. This product offers very high mechanical strength, and does not exhibit anisotropy of its mechanical properties. Moreover, such a material does not require any additional binders, and this fact also has a positive effect on its thermal stability [34].

## 5. Binders

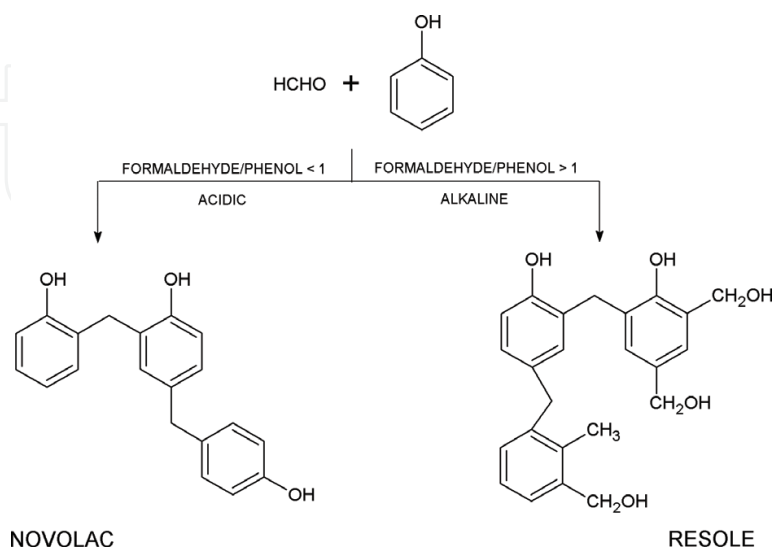
In terms of quantity, the binder is the second most significant component of an abrasive tool. It serves as a continuous phase that binds the single grains into a compact, strong composite. Abrasive composites may be based on organic binders (such as rubber, organic resins and polyurethanes) or inorganic binders (ceramics, magnesite, sintered and galvanic metals). Inorganic bonds with glass-like or vitreous structures are mostly used in grinding wheels with fine grain sizes for precision operations, while resin-bonded tools are applied in heavy metal removal processes. Ceramic and resin binders are the most commonly used types. Ceramic binders are thermally and chemically resistant and also ensure the repeatability of grinding processes. Disadvantages include their brittleness and the need to apply very high temperatures when making tools from them. Technologies for producing ceramic abrasive tools are being constantly improved. A recently introduced technology is used to obtain tools bonded with Vitrium 3 [35], which enables a smaller quantity of binder to be used, increasing the tool's

performance and also making it more porous, which enables better cooling and thus less likelihood of burning of the machined surface. Ceramic binders are used to bond superhard abrasives such as diamond and cBN. For corundum abrasives, the less expensive resin binders are more often used. These are produced with the consumption of much less energy than in the case of ceramic binders: the semi-finished product is heated at 200°C, compared with 1200°C for ceramic binders. Resin binders also offer high strength and elasticity, and give the abrasive tool good properties for polishing the ground surface. Grinding wheels with resin binders are used primarily for the cutting of materials and for rough grinding operations at high machining speeds (45–100 m/s).

A disadvantage of binders of this type is their sensitivity to the action of coolants containing bases, and to high temperature. Resin binders are most commonly based on phenol formaldehyde resins.

Phenolic resins, also called phenoplasts, have a range of properties that enable them to be used in a fairly wide range of applications. They are formed by a polycondensation reaction of phenols with formaldehyde. There are two distinct types of phenol formaldehyde resins: novolacs and resoles. The processes by which they are obtained are depicted in **Figure 5**. They differ in terms of the molar ratios of reactants and the environment in which the reaction takes place. Hardening is also carried out by a different method in each case: resole is heat-hardened, whereas novolac is a thermoplastic and must be hardened using a cross-linking agent—most commonly hexamethylenetetramine (urotropine), with the further addition of HCHO (usually in the form of paraformaldehyde).

Due to the harmful properties of formaldehyde and of the ammonia emitted when novolac is cross-linked using urotropine, new hardening agents are being sought (although up to date urotropine is still the cross-linking agent most commonly used in industry). By means of modification of novolac, for example by the introduction of epoxide and amine groups [36], it is possible to obtain resins with lower levels of emission of low-molecular-weight compounds and resulting binders with greater strength and chemical and thermal resistance.



**Figure 5.** Reactions leading to phenol formaldehyde resins in novolac and resole form, adapted from [5].

There has been increasing interest in recent years in the use of natural raw materials to produce phenolic resins [37, 38]. However, there is still only a limited number of reports on industrial applications of abrasives containing phenolic resins based on natural materials such as lignin, which currently represents a new trend in the abrasive tools industry [39]. There would therefore appear to be a need for continued intensive research to achieve further improvements in this area, related to elimination of the existing defects of binders based on resins with the partial use of phenols of natural origin. These defects include the low reactivity of derivatives of phenol from natural sources, processing problems with abrasive articles made using them, and the inferior mechanical properties compared with tools based on traditional phenolic resins. Lignin-based resins have already been successfully used in certain demanding applications, including brake blocks [40].

A very interesting alternative to binders based on phenolic resins are benzoxazine resins. These products have a wide range of mechanical and physical properties that can be tailored to various needs. Their main advantage is the absence of emissions of low-molecular-weight compounds during their cross-linking. There is also no need to add cross-linking agents. It is also noteworthy that they are produced using phenol and its derivatives, which provides the possibility of alternative use of products of natural origin. However, it was only in 2016 that benzoxazine resins were first synthesized from lignin [41]. This area of research thus remains ripe for development.

6. Fillers

Fillers are used as an auxiliary materials in the production of abrasive tools. They are usually inorganic compounds that demonstrate affinity toward both the abrasive grains and the binder holding the grains together in the substance of the tool [42]. There are several kinds of fillers, and they can be classified according to the mechanism of their action (see **Table 1**) [43].

Possible mechanism	A description of the action
I	The first mechanism involves thermal decomposition of the filler, which leads to the emission of low-molecular-weight products (such as H <sub>2</sub> O, HF or HCl). These reactions are endothermic, which means that the tool can operate at a lower temperature
II	In the second mechanism, the action of the filler results from its reaction with the worked surface, which causes corrosion of freshly removed fragments of metal. This prevents the chips from reacting with the abrasive and fusing back onto the worked object
III	The third mechanism is explained by the melting of the auxiliary material due to the heat produced by grinding, which leads to reduced friction (self-lubrication of the tool) and thus allows the tool to operate at a lower temperature
IV	In the final mechanism, fillers react with the machined surface. The reaction causes cracks to appear on the metal surface, making machining easier

**Table 1.** Examples of the mechanisms of action of different kinds of fillers.

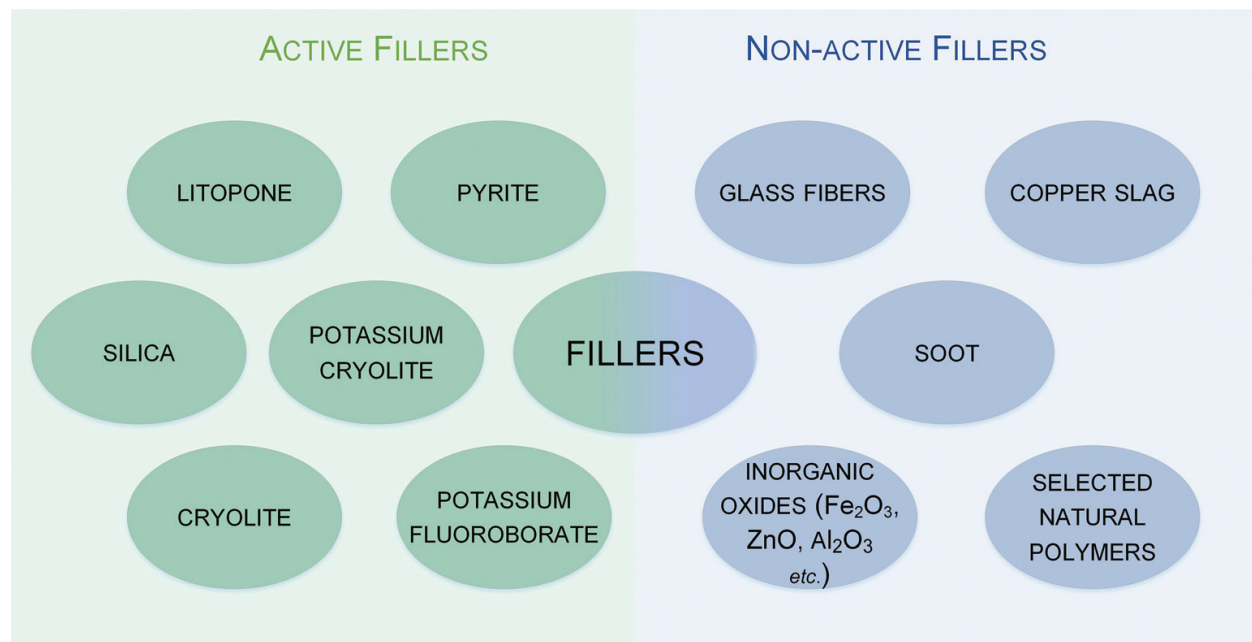


Fillers used in a tool perform several extremely important functions:

- they increase the tool's mechanical strength by improving the adhesion of grains to the binder;
- they protect the abrasive grains from the harmful atmosphere existing in the furnace during firing;
- they prevent thermal degradation of the resin on the contact surface between grain and binder;
- they cool the tool while it is operating.

Fillers are added to abrasive composites for several reasons. Most commonly, they serve merely to reduce the production cost of the tool, through the addition of an inactive filler, usually soot, cooper slag or iron oxide. It is preferable, however, to use active fillers, which serve above all to draw heat from the process, as a result of which they undergo thermal decomposition and prevent melting of the resin binder [44, 45]. Conventional active fillers have certain drawbacks, the chief of which is the emission of harmful gases due to their decomposition. Popular fillers such as pyrite ( $\text{FeS}_2$ ) and lithopone ( $\text{ZnS} + \text{BaSO}_4$ ) emit sulfur when they decompose, while potassium fluoroborate ( $\text{KBF}_4$ ), cryolite ( $\text{Na}_3\text{AlF}_6$ ) and potassium hexafluoroaluminate ( $\text{K}_3\text{AlF}_6$ ) emit fluorine and its compounds. Hence, at the present time, fillers are being sought that will combine desirable properties with limited adverse impact on the environment. The division into active and inactive fillers is shown in **Figure 6**.

It is worth mentioning that aluminosilicates such as natural zeolite have been successfully used as functional and ecological fillers [46, 47]. This is a cheap and environmentally friendly raw material, which also has a favorable effect on the thermomechanical properties of prototypical



**Figure 6.** The division into active and inactive fillers.

resin composites used in the production of bonded abrasive tools [48]. Moreover, zeolites may accelerate the cross-linking of phenol resins [48]. Since they retain a large quantity of water in their structure [49], they should not be used for superhard abrasive tools based on cBN; since at the high working temperature of such a tool and in the presence of water emitted by the zeolites, decomposition of cBN may occur.

An interesting raw material that may be used as a filler is lignin, which offers many advantages—it is of natural origin, it is renewable, and it is produced in large quantities as a by-product of the process of delignification of wood [50]. Unfortunately, due to its characteristic structure, lignin in raw state is not able to provide the required properties [51]. Its properties can be improved in two ways. One is the activation of raw lignin via its oxidation, which enables the formation of new, more active functional groups capable of reacting with the resin binder [52]. Another way to improve the thermal stability of lignin preparations is to combine them with appropriate inorganic oxides, so as to form an organic-inorganic hybrid material [53]. Addition of these innovative materials makes it possible, above all, to improve the mechanical strength and thermal stability of the final abrasive composite.

The search for new, functional fillers, which increasingly often are hybrid materials, is intensifying at the present time. The primary goal is to produce systems with improved properties, having a decisive impact on the abrasive tool that is the final product. The combination of organic polymers or biopolymers with inorganic oxides makes it possible to obtain modern additives with previously unencountered properties. Another important factor is the cost associated with the production of abrasive materials. These can be kept relatively low by using waste products for this purpose, including wastes of natural origin.

## 7. Conclusions

Abrasive technology has been developed for centuries, but there still exists a wide range of opportunities for its continued improvement. In view of the development of manufacturing industry and the dynamic state of the global economy, modern abrasive tools are becoming subject to ever more rigorous requirements as regards quality, performance, durability, cost, and impact on the environment. Future development will involve further work on each of the main components of abrasive composites, as all of these have a significant effect on the functional properties of the final product. Present trends indicate that the search will continue for new, cost-effective ways of obtaining polycrystalline abrasive materials on the nanoscale, with previously unobtainable strength properties. Attempts will also no doubt be made to modify the surface of grains with organic compounds to produce on the surface functional groups capable of reacting with the groups present in resin binders. The development of binders, in turn, will be focused on reducing their toxicity by limiting the quantities of compounds emitted during the manufacture and operation of tools, while at the same time improving their mechanical properties. An excellent alternative to traditional resin binders would appear to be benzoxazine resins, which offer very interesting physicochemical parameters, low toxicity and wide possibilities of molecular design. It is equally important to seek new functional fillers for abrasive tools, especially organic-inorganic hybrid materials. This

vision is particularly attractive in view of the possibility of producing and using many different systems combining inorganic oxides with natural polymers, which in many respects appears to be an innovative and beneficial solution. In short, the further development of abrasive composites will be driven by the concept of sustainable development, involving the improvement of functional properties while at the same time caring for the environment.

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## Conflict of interest

The authors declare no conflict of interest.

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