Preparation and Properties of Carbon Materials

for mechanical applications
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Carbon

The chemical element carbon occurs in two main ordered lattice structures: diamond and graphite. The properties of the two modifications could hardly be more different. While diamond is the hardest natural material and an insulator, graphite belongs to the softer materials and is electrically conductive.

The special lattice structure of graphite, a layer lattice, ensures good sliding properties. While the atoms in a plane are very strongly joined with each other through covalent bonds, only van der Waals forces act between different planes. Under a mechanical load, planes begin to slide along each other.
Technical carbon materials

In tribological applications, two groups of carbon graphite and electro graphite materials are widely used and are often the only technical solution. In addition to their excellent sliding properties, it is the mechanical features that distinguish these ceramic materials.

Carbon graphite and graphite materials are generally produced in polygranular and/or polycrystalline form. This means that the raw material grains of such carbon materials are composed of tiny crystallites with different orientations. Because of this microcrystalline structure, the macroscopic body often does not have the typical anisotropic crystal properties of the graphite crystal. The extreme anisotropy of the electrical conductivity or coefficient of thermal expansion is virtually non-existent, or at least greatly attenuated in polycrystalline materials. The low anisotropy of the characteristics that does however occur in polycrystalline carbon materials is linked predominantly to the pressing process, as well as the type of raw material. Thus, isostatic carbon materials, for example, have no anisotropy, while one or both sides of hydraulically pressed materials exhibit slightly more pronounced anisotropy.

Resin bonded carbon graphite supplements the range of materials for tribological applications on the polymer side. These materials are distinguished by the low cost of production in large quantities and the possibility of creating complex forms.

On the side of the carbide ceramics, graphite-filled SiC materials also bear mentioning. A special feature is certainly the silicon carbide graphite composite material SiC30 from Schunk.

Further technical carbon products can be produced using carbon or graphite fibers. These can be produced, for example, through thermal treatment of polymeric fibers, mostly polyacrylonitrile (PAN). Carbon fibers are used for reinforcing polymers (CFRP), carbon (CFC, C/C), ceramics (CMC) and metals. These composites are used primarily where the combination of high stiffness and strength with low weight plays a crucial role. Well-known applications for CFRP are sporting goods or components for the aerospace industry, which do not undergo high temperature stress. For high temperature applications, e.g. in the semiconductor industry or furnace construction, C/C materials are used. As non-brittle fracture, high-strength ceramics these materials are increasingly attractive for use in tribologically stressed components.

Furthermore, diamond and diamond-like (DLC) coatings are gaining in importance in the tribological field. The incredibly elaborate diamond coatings withstand adverse conditions, even brief dry running, and in individual applications where SiC and SiC-C composite materials cannot be used, there is no other alternative.
Manufacture of carbon graphite and graphite materials

The production of the materials is carried out in line with production methods that are based on classic ceramic technologies. At Schunk, some of this is achieved through fully automatic processes and monitored online.

**Material processing and mixing**

The melting point of carbon is above 4000 °C at a pressure of 100 bar. Carbon sublimates at lower pressures. Thus, technical carbon cannot be produced by simple sintering processes. Therefore, the production of carbon graphite and graphite materials occurs in a filler/binder system. Raw materials such as petroleum cokes, pitch cokes, carbon blacks and graphites are milled to defined grain size distributions. These fillers are then mixed, preferably on twin-screw extruders at elevated temperature with a thermoplastic binder. Alternative coal tar pitch or petroleum pitch and synthetic resins can be used for this purpose. The mixture is then ground to a powder for the shaping process.

**Shaping**

The ready to press mixtures are formed into so-called green parts through unidirectional die moulding or isostatic pressing.

**Carbonizing parts**

The green bodies are then carbonized. A variety of furnaces with specific heating rates, maximum temperatures and furnace atmospheres are used for this purpose, depending on the material, dimensions and the desired material properties. During the carbonization process pyrolysis takes place, i.e. decomposition of the binder into volatiles and carbon. The volatiles produce an open pore structure. The binder remains in the molded article as so-called binder coke and ensures high strength and hardness. These materials are referred to as carbon or carbon graphite.

**Graphitization**

Carbon graphites are partially amorphous and a little graphitic. To produce graphite materials, carbon graphites are graphitized at temperatures of up to 3000 °C. At Schunk this is mainly achieved through the Acheson process. Here, the material to be graphitized is packed between two furnace electrodes and positioned as a resistor in the secondary circuit of a transformer. The material is thus brought to the graphitization temperature by resistance heating. Larger graphitic areas are thus formed by recrystallization. Such electrographites generally demonstrate good sliding properties, have low electrical resistance, high thermal conductivity and improved corrosion resistance compared to carbon graphites.

**Impregnation**

The porosity of carbon graphite and graphite materials can vary in a wide range. This porosity can be reduced or even eliminated through impregnation. Many tribological applications require impermeability to fluids; other targeted material properties can also be influenced by the impregnation medium. At Schunk, impregnation usually takes place via a vacuum-pressure process. Impregnation can be achieved with different resins, metals such as antimony or copper and with inorganic salts. Densification with carbon is also possible.
Properties of carbon graphite and graphite materials

Porosity

The production-related porosity of carbon graphite and graphite materials leads to a certain permeability to fluids. For some uses the existing pores are not a problem. However, porous materials are unsuitable for sealing elements such as seal rings for mechanical seals. The open porosity of carbon graphite and graphite materials can be reduced/completely closed by means of impregnation (see previous section on „impregnation“).

Bulk density

Because of the existing pores, it is common to specify the apparent density or bulk density. This can vary from 1.5 to 3.3 g/cm³ depending on initial porosity and impregnation. Carbon components are extremely light.

Chemical resistance

Carbon graphite and graphite materials are distinguished within the group of corrosion-resistant materials by their excellent chemical resistance. For details, please see our brochure 39.12 on chemical resistance.

Temperature resistance

In an oxygen atmosphere, carbon is oxidized at high temperatures. In air, this oxidation occurs for carbon graphite materials from about 350°C and for graphites from 500°C. Through special finishing operations, the temperature resistance of graphite in an oxidizing atmosphere can be increased to over 600°C. In a non-oxidizing atmosphere, the temperature resistance of carbon graphite and graphite is determined by the treatment temperature during the production process and thus is about 1000°C or > 2500°C. For resin and metal impregnated materials, thermal stability is limited by the decomposition or melting temperature of the impregnating agents used. The temperature limit for resin-impregnated materials is >200°C depending on the resin used.
Strength

Carbon graphite and graphite materials have a comparatively low tensile and flexural strength, but a higher compressive strength. In contrast to plastics or metallic materials, their strength does not decrease with increasing temperature.

In constructions with carbon graphite and graphite materials, typical ceramics must be considered to have a certain brittleness. Because of this greater brittleness compared to conventional metallic materials, the strength of these materials is not to be characterized by details of tensile strength and elongation values. Rather, it is customary to provide as parameters the bending and compression strength and the modulus of elasticity.

Carbon graphite is superior to electrographite in terms of strength. Electrographite, on the other hand, has a somewhat lower brittleness. By impregnation with synthetic resins or metals, strength, elastic moduli and hardness can be significantly increased.

Hardness

Schunk is measuring the hardness values HR5/40, HR5/100 and HR5/150 for carbon materials. A 5-mm steel ball with 98 N preload and 294 N, 883 N or 1373 N additional load is pressed into the body to be tested. After removing the additional load, the remaining penetration depth is a measure of the hardness HR5/40, HR5/100 of HR5/150 (dimensionless), which is read according to the B-scale of Rockwell hardness testers. To facilitate comparison with the hardness values of other materials, we have included the Brinell Hardness in our „Characteristics - Standard materials“ brochure (30.14) as well as the Rockwell Hardness (RH).

For continuous quality control we do not measure hardness using the Brinell method, since this is permissible only if the surface of the porous material is polished. Dynamic hardness measuring methods are in our experience less suitable because of the structure of the material. Moreover, the use of Shore hardness values alone is problematic because the measured values are heavily dependent on the device used.

Thermal conductivity

In Table 1, the typical thermal conductivities of carbon graphite and electrographite compared to other common materials are summarized. Carbon graphites achieve the conductivity of stainless steels, and electrographites are distinguished by even higher thermal conductivities.

Coefficient of thermal expansion

Another important feature that must not be forgotten in design using carbon materials is low coefficient of thermal expansion in comparison to metals. With coefficient of thermal expansion in comparison from 2 to $6 \times 10^{-6}$/K it is smaller than that of metals by factors.

### Table 1: Thermal Conductivity

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity $+20, ^\circ C$ W/m°K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrographite</td>
<td>40-130</td>
</tr>
<tr>
<td>Carbon graphite</td>
<td>8-17</td>
</tr>
<tr>
<td>18/8 Chrome-Nickel Steel</td>
<td>15</td>
</tr>
<tr>
<td>Grey Cast Iron</td>
<td>45-60</td>
</tr>
<tr>
<td>Copper</td>
<td>395</td>
</tr>
<tr>
<td>Bronze SnBz 12</td>
<td>38</td>
</tr>
<tr>
<td>Cast Chrome Steel</td>
<td>19</td>
</tr>
<tr>
<td>Sintered Ceramic (Al$_2$O$_3$)</td>
<td>21</td>
</tr>
<tr>
<td>Silicon Carbide</td>
<td>BD-130</td>
</tr>
</tbody>
</table>
Thermal shock resistance

Thermal shock resistance is excellent for carbon graphite and particularly for electrographite materials. It can be defined as the quotient of the product of strength and coefficient of thermal expansion and the product of Young's modulus and thermal expansion coefficient.

Sliding properties

Graphite, whether natural graphite or electrographite, has self-lubricating properties by virtue of its special crystal structure. As graphite is always used as a component in the production of carbon graphite materials for bearings and sealing elements, an important part of these materials consists of dry lubricant, as well as electro-graphite. Even without additional liquid lubricant, the friction coefficient between carbon materials and the counter material with perfect sliding surfaces is relatively low. Generally, valid information on the friction coefficient cannot be determined due to the widely differing operating conditions. In dry running with gray cast iron or steel, a friction coefficient in the region of $\mu = 0.1$ to $0.3$ can be expected. In the presence of liquids or vapors, whereby the type of liquids or vapors is of minor importance, the friction coefficient is reduced significantly in the mixed friction area to $\mu < 0.1$. Indicators on the course of the friction coefficient between carbon graphite and gray cast iron or steel in dry operation are provided in the following four diagrams.

![Graph 1: Variation of the coefficient of friction $\mu$ during running-in](image1)

![Graph 2: Coefficient of friction $\mu$ as a function of the mean sliding speed](image2)

**Test conditions:**
- Thrust bearing
- Carbon grade: FH44Y
- Diameter of carbon ring: 80.5/57.5
- Face area: 25 cm$^2$
- Counterface material: Cast iron (fine finished)
- Temperature at the running surface: $\sim 100 \, ^{\circ}\text{C}$
- Specific loading: 1N/mm$^2$
- Mean sliding speed: 0.8 m/s

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- Specific loading: 1N/mm$^2$
The first diagram, in which the friction coefficient is plotted over the run time, shows that this decreases with the progress of the running-in and an associated progressive smoothing of the sliding surface, and then stabilizes at a low level. Of far greater importance however is the fact that the friction coefficient is dependent on the sliding speed and the specific load. Tables 2 and 3 show this dependency for the carbon graphite material -FH44Y-.

Table 4 shows the dependence of the friction coefficient on the specific load at two constant running speeds using the example of the resin-impregnated carbon graphite material -FH44Z2-. Of particular note is that the carbon materials exhibit excellent resistance to wear at low friction coefficients too.
Design notes for fine-grain carbon machine parts

Since all sliding elements made by Schunk Carbon Technology are produced according to customer drawings and/or customer specifications, the designer is not bound by standards or standard norms of dimensions or materials.

When designing bearings and sealing elements, the ceramic properties of carbon graphite and graphite materials described above are to be observed.

It is therefore advisable to contact us during the new component design stage to avoid designing components that are inconvenient or impossible to produce.

The geometries are machined typically from pressed semifinished products. Virtually all machining methods can be used: e.g. sawing, water jet cutting, turning, milling, drilling, grinding, honing, lapping and polishing. The wall thickness should not be less than 3 mm, if possible. For round parts, the wall thickness should be 10-20% of the inner diameter, depending on the size of the components. The length of the components can be up to double the outside diameter. Furthermore, a division into two or three pieces may have to be performed. Deep and narrow bores should be avoided. As a rule, an inside diameter tolerance of IT7 and an external diameter tolerance of IT6 can be complied with. Because of the risk of fracture, it is advisable to refrain from large cross-sectional changes. An alternative would be to divide the part into several pieces with different wall thicknesses. Sharp edges should be chamfered.

If components made of carbon graphite or graphite materials must be mounted in metallic casings or secured against rotation, screws and wedges are eliminated due to the notch effect. The first choice should be a press- or shrink-fit. If this is insufficient, pinning can be used. It is important to ensure that this happens in an unloaded area and the carbon component undergoes no tensile stress by the thermal expansion of the pin. Carbon moldings are to be fastened in metal frames or directly in the housing when pressing or shrinking, preferably over the entire length to support it. In cantilever installations correspondingly large wall thicknesses should be used.
Resin bonded carbon materials

These materials consist of carbon and/or graphite-filled phenolic resin. Different compositions reflect the different requirements in respective applications.

A great advantage of these materials is the possibility of applying plastic molding processes, which enable cost-effective production in large quantities. In addition to the injection molding process at Schunk, injection-compression molding and the unidirectional pressing applied in tempered dies are also used for these materials. Since the tool costs of injection molding are considerable, suitable areas of application include bearings, sealing rings and pump parts, which are needed, for example, in the automotive industry in large quantities. The temperature resistance up to 180°C and the temperature expansion coefficient within the region of metallic materials bear mentioning here. Thereby, it is possible to injection-mould around inserts or the material itself as an insert part. Applications at up to 250°C have already been achieved, and even the production of all-carbon materials is possible.

The minimum wall thickness is determined primarily by the tooling and can be as low as 0.5 mm. The maximum wall thickness of a component should not exceed 10 mm, otherwise efficient production can no longer be achieved due to the longer curing times of these thermoset materials in the heated mould cavity. Within the tool, a tolerance of IT9 to IT10 can be used as a reference value. For measurements in mould parting system of the tool a tolerance of ≈ 0.1 mm can be maintained. All tolerances are dependent on numerous parameters, such as material, component geometry, number of mould cavities and thermal post-treatments.

The definite tolerances should be determined after the first production trials via statistical analysis. For compliance with important functional tolerances, process control methods are used as a quality assurance measure.