Cutting tools from superhard materials. Part I. Diamond blades

Narzędzia skrawające z materiałów supertwardych. Cz. I. Ostrza diamentowe

PIOTR CICHOSZ
MIKOLAJ KUZINOVSKI
MITE TOMOV*

DOI: https://doi.org/10.17814/mechanik.2017.8-9.99

The properties of super-hard materials such as diamond and regular boron nitride, and their application on cutting blades. Discussed are examples of blade tools from these materials in the aspects of production process efficiency and economical advantages gained by using these tools. The first part of the article deals with materials and tools with diamond blades and the other – with the blades of a regular boron nitride.
KEYWORDS: diamond, boron nitride, tools, cutting

Super-hard materials include diamond and regular boron nitride. According to the valid PN-ISO 513:1999 standard, polycrystalline diamond is designated DP and regular boron nitride is BN. However, widespread use, not only in industrial environments, but also academic notations are used: PKD and CBN (CBN). In accordance with the cited standard single crystal diamond is marked as DM.

The article will be used in accordance standard assay. It should be noted, however, that DIN ISO 513: 2014-05, which refers to the types of carbide and regular boron nitrides, is becoming increasingly common in publications and information materials of many tool companies (Figure 1). For example, the designation BN replaced three symbols BL (sinters with a low content of boron nitride), BH (sinters with a high content of boron nitride) and BC (sinters with a high content of boron nitride, but coated). Introduced a new designation PD polycrystalline diamond without binder phase.

These materials are much harder than other cutting tools. In addition, they are very resistant to abrasion and therefore tools from these materials have long shelf life. Unfortunately, blades of super-hard materials are usually several times more expensive than blades from other, more common materials such as carbides, cermets or ceramics.

Despite the high price, under some processing conditions they may exhibit good technological results and their use is economically justified. That is why tools with super-hard materials are becoming more and more popular, especially for large scale production and high automation where durability is very desirable.

* Prof. dr hab. inż. Piotr Cichosz (piotr.cichosz@pwr.edu.pl) – Katedra Obrabiarek i Technologii Mechanicznych, Wydział Mechaniczny Politechniki Wrocławskiej; prof. dr inż. Mikolaj Kuzinovski (mikolaj.kuzinovski@mf.edu.mk), doc. dr inż. Mite Tomov (mite.tomov@mf.edu.mk) – Faculty of Mechanical Engineering, Ss. Cyril and Methodius University in Skopje, Macedonia

Sources say that the super-hard materials represent only a few percent of the total tool materials. However, if you consider the percentage of the volume of removable material, it would certainly be much larger.

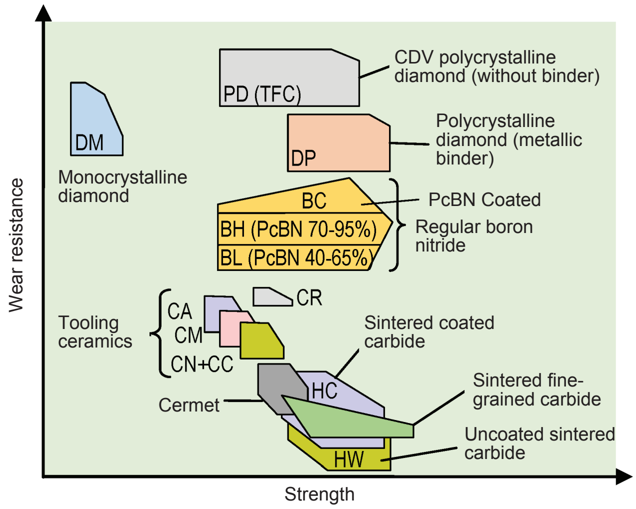


Fig. 1. Tooling materials according to DIN ISO 513: 2014-05: CR – Al_2O_3 reinforced alumina ceramics, CA – Al_2O_3 oxide ceramics, CM ceramics – CN3 – Si_3N_4 silicon ceramics, CC coated ceramics

Super-hard material – diamond

Natural monocrystalline diamond achieves a hardness of 8000÷10 000 HV and is the hardest known material. A very important feature of the diamond is stiffness. Modulus of elasticity of diamond exceeds the modulus of elasticity of other known materials. It is approximately three times larger than the silicon carbide and boron carbide elastic modulus and much larger than carbide [1].

A diamond is pure carbon crystallized in a regular grid spatially centered. Originally the cutting blade and dressers for grinding wheels used single crystals of diamond having a disqualifying blemish in applications jeweler. The oldest instances of the use of the diamond dates back to 300 years BC Diamond then used for engraving. Today, natural diamond monocrystals are used sporadically on cutting edges because of their rarity, high price and high supply of synthetic diamonds, mainly because of the appearance of diamond sintered diamonds, which have many properties much more advantageous than monocrystals, especially in their shape.

Diamond as a tool has the following advantages:
- very high hardness and abrasion resistance;
- low thermal expansion, roughly less than carbide, which is particularly important in the precise and precise machining where it is used;
- very good thermal conductivity, which results in a significant reduction in the maximum temperature that can occur on the cutting edge work surfaces (this reduces the intensity of almost all tool wear, such as diffusion, adhesion, oxidation, abrasion or graphite); However, good thermal conductivity also has bad sides, namely, it causes a more intense heating of the tool, which can affect its thermal elongation and make it difficult to control the machining accuracy. This unfavorable phenomenon largely counteracts very low thermal expansion of the diamond;
- possibility to obtain a smooth working surface of the blade and cutting edges of small gaps, even for large positive rake angle, which is important in treatments of precision, in particular in nanotechnologies, and treated composites;
- ease of shaping a very smooth surface items, including aesthetic, and it is maintained for a long tool life; this is due to, among others, poor wettability of most non-ferrous metals, a low tendency to adhesiveness, which reduces the build up of accretions or prevented so-called incurring the surface.
- diamond also has many disadvantages, which greatly reduce its use in cutting, for example:
- strong affinity with iron, nickel, cobalt and their alloys, causing the carbon atoms to dissolve intensively, increasing the diffuse wear (hence the processing of these materials with diamond blades is not recommended but cobalt easily moistens most of the components used for cutting materials, including diamond, due to the high melting temperature – 1 495°C – ideally suited for bonding sinters); single crystals and sintered diamond is used for machining of very hard materials, composites with hard particles or fractions of reinforcing fibers, as well as for the treatment of non-ferrous metals or alloys thereof, especially when a strong need to maintain very long tool life;
- graphitization, depending on the purity of the diamond may take place already at a temperature above 700°C, which limits the range of acceptable cutting speed;
- low diamond resistance to oxidation even though its melting point is ~3750°C (in the atmosphere of pure oxygen it burns at about 720÷800°C, and in the air atmosphere – at a temperature of about 850÷1000°C, forming carbon dioxide). regardless of the temperature of the cutting operation of the tool should not exceed 700÷800°C [18];
- dependence of mechanical properties on the planes of the highest packing of carbon atoms in which the crystal is extremely hard and at the same time very fragile and easily cleaved – hence the need to orient the crystal in the blade so that the cutting forces do not work in that plane;
- very brittle and associated with low mechanical shock resistance;
- Low bending strength (~300 MPa) can prevent the use of large sections of cuttings, resulting in large, dynamically impacting cutting forces; this restricts obtaining high volumetric treatment;
- difficult shaping mainly caused by hardness and brittleness of diamond, virtually ruling out mechanical interactions in step roughing and shaping; no electric conductivity of the diamond eliminates electro-discharge and electrochemical treatment; good thermal conductivity and transparency of its crystals make it difficult to apply to the development of lasers.

In recent years, there have been hybrid machines, combining laser processing and water jet, designed for efficient diamond shaping. Functional diagram of the machine shown in fig. 2. The main idea lies in the fact that a coherent, parallel stream of water is used – as a kind of optical fiber – to transmit photon beam in the zone of their impact on the molded article.

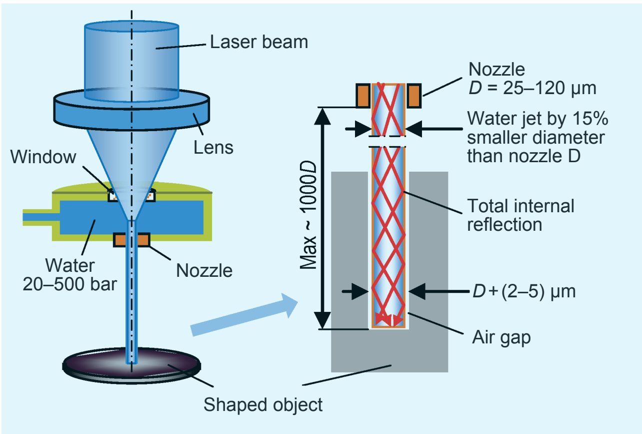


Fig. 2. Diagram of diamond hybrid treatment (by SYNOVA)

Hybrid diamond processing has several advantages, including:
- much more shaping efficiency than laser alone,
- constant cut width is even relatively deep, which results from the „parallelism" of the light beam caused by the total internal reflection of the water jet,
- no need for precise focusing of the beam,
- cutting depth to a few centimeters,
- 3D cutting capability,
- water cooling avoids thermal damage and changes in the material and produces good quality molded surfaces,
- the laser resonator generates a suitable wavelength which is preferably absorbed by the diamond,

● due to the high kinetic energy of the water jet the molten material is easily removed from the slits, even deep and with parallel walls.

The disadvantage of this method is the relatively high price of machine tools.

Synthetic diamond is a strong competitor of natural diamonds, not only in the area of powders and the resulting frit, but also in large size monocrystals. Synthetic diamonds have comparable utility properties for natural diamonds, but they are much cheaper. Contemporary diamond manufacturing techniques allow the synthesis of crystals up to 10×10 mm. Attempts are being made to return to the use of monocrystalline diamond, the synthetic time, the cutting blades. Quite a wide range of blades DM company offers TIZ TOOLS [16]. Single crystals are vacuum-brazed to carbide substrates.

The first diamond synthesis was made in the early fifties of the last century. Today, there are several methods of its manufacture and sintering. Quite detailed discussion of these issues [8]. Depending on the method used, especially the binder, one can obtain significantly different materials from the materials.

Sintered diamonds have many variations in the content of diamond grains, the size and variety of the grains, the binding phase, and even the absence of them. Many companies on the blade blanks, indexable inserts, as well as ready-made tools has a rich assortment of these products.

The most commonly used binder phase sintering diamond is cobalt. It is good wettability, improves the strength properties and – even added to the sinter in just a few percent – as a metal causes the sinter to start to conduct electricity. This is quite important because of the possibility of cutting and shaping of extremely hard materials and difficult-not only lasers, but also electro and electrochemical treatments, or both.

Sintered diamonds are usually bonded in a bonding process with a sintered carbide backing. Are available cemented carbide rings with a diameter even more than 100 mm from the applied diamond layer having a thickness in the range of 0.3 to 1.5 mm. The total thickness of the disc may be 1.6÷8 mm. The outer surface of the diamond is mostly polished to provide better chip flow and good surface quality. The diamond sinter does not allow to obtain such good quality in terms of the friction of the cutting edges like a monocrystalline. Therefore, where very smooth surfaces and high machining accuracy are required, for example in nanotechnologies, diamond-shaped blades or very fine grits are used [17].

Application of a diamond layer on a substrate of cemented carbide offers many advantages (Fig. 3). First, it is approximately three times more resistant to bending than the diamond itself, which makes the blade more durable. Secondly carbide is about half the size

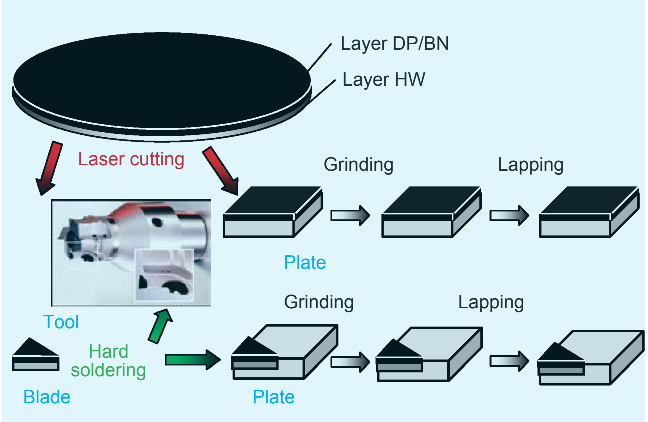


Fig. 3. Production of tools with blades from super-hard materials

of the steel coefficient of thermal expansion, which reduces shear stress on the soldering tip. You have to remember that the sintered diamond in relation to carbide also has several times lower coefficient of linear expansion. Thirdly brazing carbide with steel is much simpler and more reliable than a diamond with steel.

Soldering to the tool body of the diamond blade itself or its sinter, also due to significant differences in warmth, is quite difficult and can cause a large number of deficiencies [8]. For these materials, very expensive laser-based vacuum devices and special silver-based feathers, containing indium and titanium, are used to brazing these materials, which improves solderability, allowing for a more durable and durable diamond engagement with the tool body [8].

Blade of super-hard materials are placed in a variety of ways replaceable cutting inserts made in the ISO standards (for example, fig. 4).

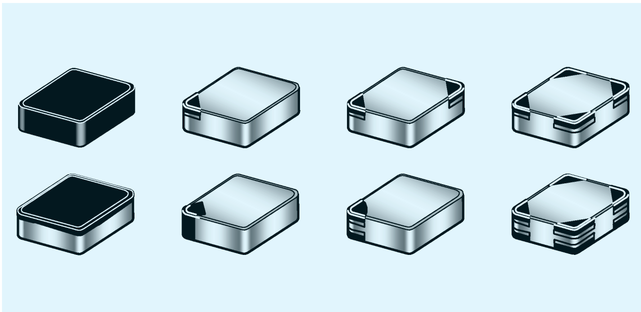


Fig. 4. Examples of placement of blades made of super-hard materials in interchangeable plates [6]

Due to the fact that the diamond sintered particles are formed from randomly oriented crystals, the blades do not exhibit strong anisotropic mechanical properties.

Sintered diamond fractions of 2, 10 and 25 μm are used for sintering, and larger grains are also mixed with the smallest to achieve a better diamond concentration (fig. 5).

Smaller grains (2 μm) and diamond concentration ~90% have higher hardness and slightly lower cutting edge strength. They are used for finishing work. They

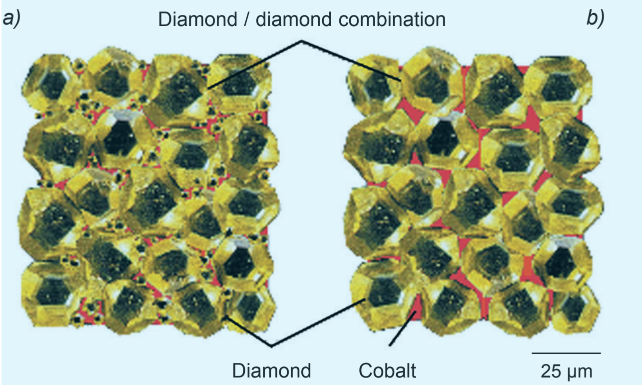


Fig. 5. Possibilities of packing diamonds in a sinter: a) two-grain fractions ~ 2/25 µm, b) single grain fraction ~ 25 µm

are used in drill bits, and to a lesser extent – in milling cutters [11, 13].

Sinters having an average particle size (10 µm) and a diamond concentration ~92% are versatile and are used in treatments accurate average.

Coarse-grained sinters (~25 µm) and a concentration of ~94% are highly resistant to wear, can work under severe conditions of rough, high speed, without the use of treatment fluids. They are suitable for milling.

Composite granules (2 and 25 µm) can have a diamond concentration of ≥95%. They combine high abrasion resistance and very good cutting edge quality. They tolerate harsh environments. Can be used on cutters. They are good at milling aluminum alloys with silicon content >14%.

Depending on the needs of the puck with the applied layer of sintered diamond cut blanks blades that solders in the tool body, a replaceable cartridge or indexable plate (fig. 3 and fig. 4). Cutting the full disc dozens of blades by wire EDM drill lasts up to several hours. The cutting process can speed up several times, if applied to the laser beam. However, too much shaping can lead to significant degradation of the temperature of the sinter cutting zone, which must then be removed using lower machining parameters or other technologies. This applies to both varieties of cut. Tool components with sintered blanks are subjected to finishing work that gives them the desired shape, dimension, proper smooth work surface and the friction of the cutting edges.

Because of the poor weldability of titanium alloys used sometimes tool bodies to reduce their mass, for securing the blade segments adhesives are used and further mechanical attachment [13].

Examples of tools with sintered diamond blades

Drills with sintered diamond blades are made in such a way that the blanks on the blade are cut out of a layered disc in which the diamond sinter is between two carbide plates (Figure 6). The cut shape of the blade is soldered to the steel body, and then the carbide layer is sanded from the sites of the future attack surface, exposing the sintered DP material (fig. 7a). Double sided support of sintered layer with carbide insert reinforces it and facilitates brazing.

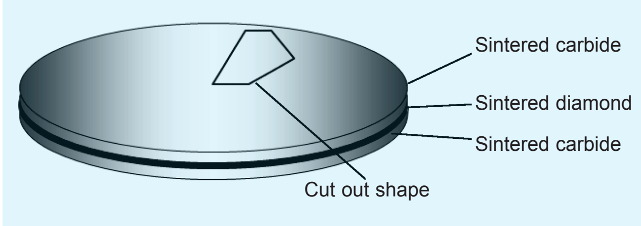
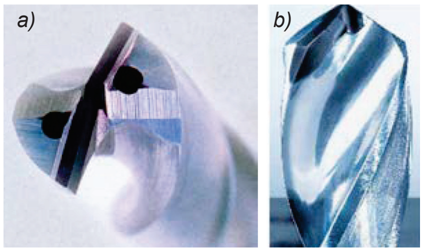


Fig. 6. Example of cutting a drill bit segment from a disc with a sintered diamond

Another technology of placing a sintered diamond used e.g. at MAPAL, is a direct sintering of the diamond layer to the body of cemented carbide (fig. 7b) or retrofitting drill segments sintered only at the corners. The shear itself and its surroundings are made of a material such as a drill bit, that is, of the carbide, which at the lower cutting speeds that occur near the axis of the drill, performs its role no worse than the much more brittle diamond sinter.

It is important to note not only the significant differences in their coefficients of thermal expansion α, but also that the relative proportions of these coefficients vary at different temperatures [17]. For DP at 20 °C, the coefficient $\alpha = 1.3 \times 10^{-6}$/K, and at 700 °C, $\alpha = 3.9 \times 10^{-6}$/K; For carbide sintered at 20 °C, $\alpha = 4.5 \times 10^{-6}$ /K, at 700 °C, $\alpha = 5.2 \times 10^{-6}$/K. This can cause thermal stresses in the soldering stage. These stresses may adversely affect the stresses generated during the shaping of the blade and/or the cutting process, resulting in delamination of the material and cracks. Therefore, laser soldering vacuums and special silver-based binders, containing indium and titanium, are used for brazing, which ensure the correct and reliable engagement of the diamond with the tool body [17]. This problem is negligible when brazed to the tool body components blades cut with a DP of sintered cemented carbide substrate (fig. 7a).

Fig. 7. Drills with diamond sintered blades: a) JEL, b) Mapal



In small-diameter pinwheels, it is very difficult to solder the cutters made of cut diamond segments, mainly because of a significant weakening of the tool body core. Therefore some companies instead of blades solder directly sinter the diamond part with the carbide body (fig. 8). You can then make tools with very small diameters. Similarly, the blades of regular boron nitride are dealt with, as will be discussed in the second part of the paper.

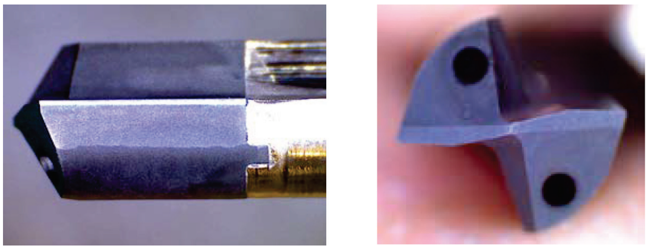


Fig. 8. Drill equipped with a diamond sinter bit directly to the tool body, D = 2.5 ÷ 6 mm (Mapal)

Polycrystalline diamond blades obtained by CVD gas plasma vapor deposition technology are also produced. A pure diamond layer, without the use of a thin film diamond (TFD) film thickness of up to 0.5 mm [4] is obtained. They are then brazed in a vacuum indexable about the ISO/ANSI standards. The blades obtained by this method are characterized by better quality and sharpness of cutting edges from DP blades, the possibility of shaping surfaces with less roughness and less cutting resistance, which are advantageous for the processing of flimsy, thin-walled objects. Noteworthy is also the manufacturers declared much longer tool life compared to those with blades from the sintered DP.

In order to reduce the weight of tools, especially those for large-scale (200÷350 mm) bulkheads, Mapal has used a welded multi-stage reamer housing in which slots are mounted mechanically with diamond sintered blades (Figure 9). guide bars, also of diamond sinter. Lightweight tool design in many cases facilitates or enables automatic tool change between the magazine and the spindle of the machine.

Despite the large dimensions, the tool guarantees very high accuracy of the holes (cylindrical, roundness <0.005 mm, accuracy class IT6÷7).

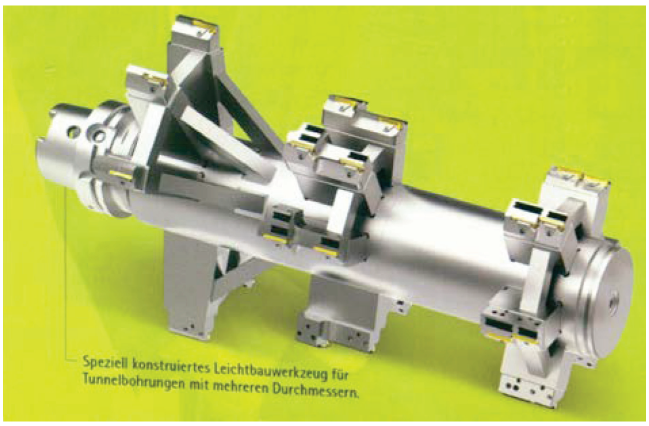


Fig. 9. Team reamer of a lightweight construction for large multi-stage holes machining (Mapal)

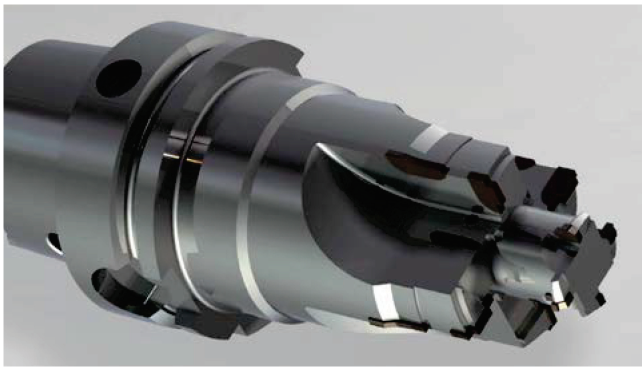


Fig. 10 shows a tool with blades from DP for processing a composite internal combustion engine head cover

Fig. 11 shows a tool with DP blades for precision machining of a multi-stage hole for fixing camshaft bearings. The hole forming machine is located on a carbide-tipped extension, equipped with screw guides that provide not only high stiffness, but also very good guidance. This tool has a centrally located special screw for resilient blade diameter adjustment as well as guide rails. You can also accurately correct the second degree of tool diameter by changing the angular position of the spring-mounted segments with the cutting edges.

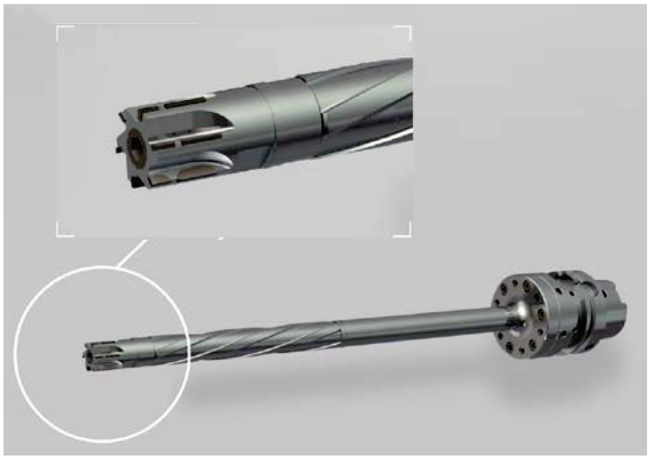


Fig. 11. DP tool (Gühring)

Fig. 12 shows a tooling tool for machining a multistage hole with a diameter of 280 mm. It is equipped with diamond sintered blades, located in cartridges for very precise blade setting. Together with guide rails it allows to make dimensions in IT6 class. Note that the placement of the blades is not directly in the tool body, and that through adjustable cartridges does not force the cutting edges to be precisely shaped relative to the tool grip portion, as this can be accomplished by setting. Such pads can also be used to facilitate the regeneration of the tool.

Figure 13 shows a DP tool assembly for machining a multistage hole. The holes are made in H7 class, with a rotational speed of 11600 rpm. The number of workpieces between tool regenerations is 250000 pieces.

Fig. 12. DP tool (Gühring)

In many cases, tools are available with a built-in bell tower. Such tools can circularly maneuver axially-symmetrical outer surfaces or, for example, shape pivot surfaces, working as external dredgers/reamers. An example of this second type of tool is shown in fig. 14.

DP blades of these tools allow machining aluminum alloys with very high cutting speeds.

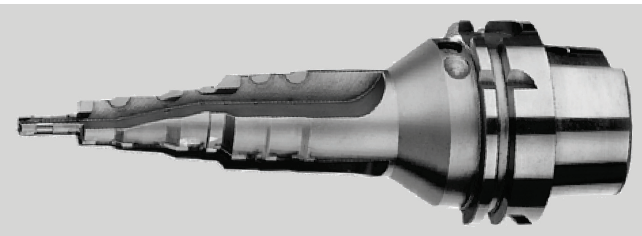


Fig. 13. DP blade tool (Mapal)

Fig. 14. External dredger with DP blades (Gühring)

Large revolutions cause significant centrifugal forces that expose the bodies of these tools to deformations, which may hinder the behavior of usually quite tight machining tolerances. This can be counteracted by ring reinforcement (fig. 15).

Fig. 15 shows a bell cutter with DP inside the „closed structure". Such tools are characterized by high stiffness, which allows to increase the machining parameters, work without vibration and maintain a very good surface quality (fig. 15a).

Fig. 15. Blade with DP blades for circulating external surfaces; a) cutter, b) shaped surface (Mapal)

Bell tools with internal blades, sometimes with a multiplicity of numbers, can greatly complicate the technology of precision edge and work surface design. It usually eliminates electro-erosion by wire drilling and grinding due to the difficult availability of space.

Some companies, such as Mapal, have mastered the technique of precision shaping of the superlative surface with a laser beam falling on it tangentially and perpendicularly. This tool has been presented.

Fig. 16 shows an example of fixing and adjusting the cartridge in the tool body. The adjustment can be done in different ways [6, 12], e.g. as shown in the drawing, using wedges inserted between the tool body and the cassette, with pivots with eccentric surfaces and, very often, with swivel resilient blade cassettes. This is especially advantageous for extremely heavy working conditions and frequent blade changes.

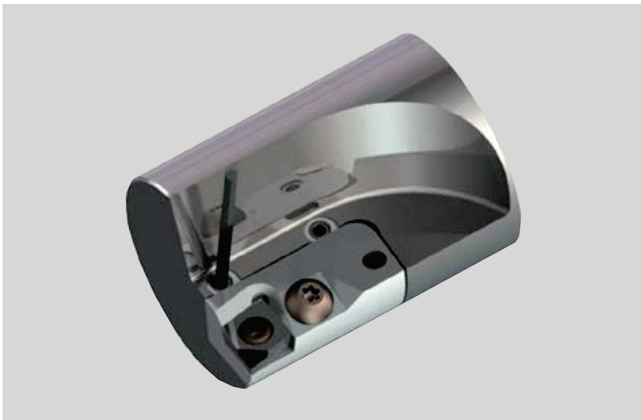


Fig. 16. Gühring tool holder with removable inserts with super-hard blades

Chip breakers

Diamond sintered blades usually have a very smooth, planar rake surface located at a positive or zero rake angle. Most of these materials are non-ferrous metals with low cutting resistance that can be formed at very high speeds. Both of these factors cause a very good separation of the chips on the one hand and, on the other hand, they can have an unfavorable form.

The ribbon, striking at a very high speed on the surface to be treated, can damage it and even break into it and become fatigued. In addition, continuous swirling can significantly impede or even prevent processing, especially when it is performed without supervision or with limited supervision of the worker. Exiting from this situation could be the formation of a breaker on the rake surface. However, diamond sinter is one of the worst machinable materials. Therefore, such chip breakers are formed only when necessary, and this is most often done by laser drilling.

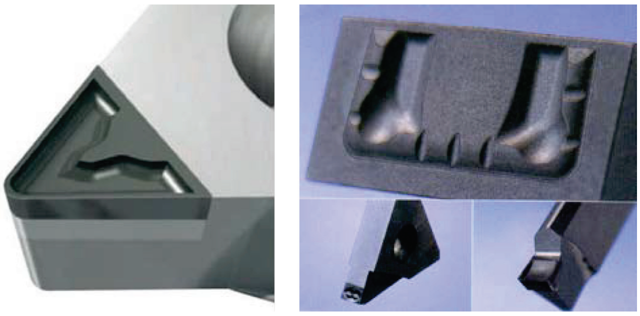


Fig. 17. Diamond sintered blades with laser-shaped choppers [10, 16]

Examples of interchangeable blade blades with such breakers for cutting and grooving are shown in fig. 17.

Sometimes chip breakers are made in overlapping version, they can simultaneously perform the function of protecting the tool body against abrasive action of chips (fig. 18).

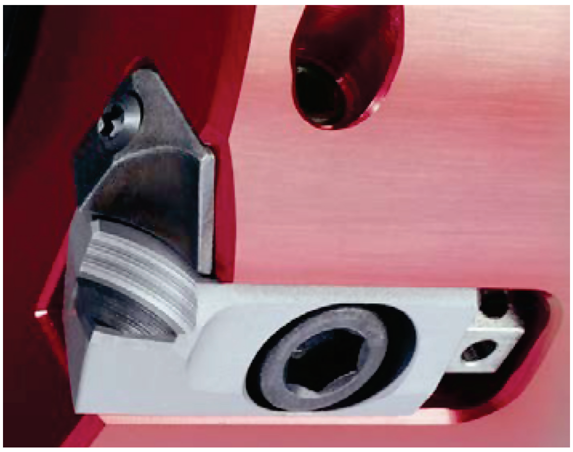


Fig. 18. Diamond sintered cassette/insert for cutter heads with chip overlap (Mapal WSS)

An interesting solution to the problem of removing chips from the cutting zone, especially from the narrow gap between the cutter head and the machined surface, was proposed by Mapal (fig. 19a) and Gühring (Figure 19b). Shavings that originally came into the front of the head caused scratching and milling of the workpiece. In the present solution they are directed to specially shaped pockets located in the diamond blade mounting cassettes. An additional advantage of this solution is the protection of the tool body against abrasion by high-speed chips. In the chip chambers near the cutting edges there are channels feeding the processing fluid directly into the material separation zone. The centrifugal pump increases the efficiency of the delivery of the machining fluid, and also expels chunks from the chambers outside the tool's lateral surfaces.

Fig. 19. Chip cutter head with chip dispensing chambers: a) Mapal solution, b) Gühring-Hollfelder solution

Diamond coatings

Diamond coatings are manufactured using CVD (chemical vapor deposition) technology, usually at high temperatures, so they are not applied to high-speed steels that could be tempered. Diamond coatings are formed by the decomposition of $C_2H_4 \rightarrow C_2 + H_4$ under very low pressure, plasma and pulsed electric fields. Hydrogen is pumped out of the chamber, while the coal is crystallized on the working surfaces of the blades in a regular spatial centered grid.

Multilayer coatings are also being produced, with alternating nano-sized structures (fig. 20). This contribu-

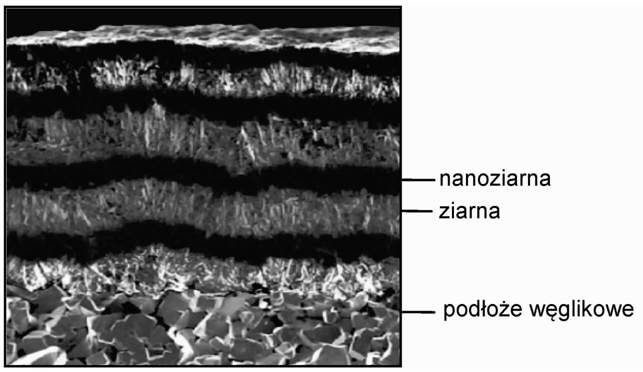


Fig. 20. View of the breakthrough of the multi-layer diamond coating CC Dia®Tiger (CameCon)

tes to a greater relaxation of the stresses between the layers of the diamond, less susceptibility to fracture, and also allows for a very fine structure on the outer surface. This structure improves chip flow and allows for less edge friction. Because the coating is pure diamond, the consequence is the lack of electrical conductivity, which excludes electrically assisted processing.

A disadvantage of diamond-tipped blades is that, as with other anti-wear coatings, the radius of the rounding edges (Fig. 21) is increased. In the meantime, diamond cutters are usually required sharp edges, which can be easily achieved on diamond sintered diamonds, and much more difficult on carbide blades with a coating of a certain thickness. Where complex tools are used, for example in drill bits and mandrel cutters, it is recommended to make them as solid carbide and to apply diamonds of very low thickness, even in the order of 1 μm. This is a compromise between easier tooling and good material separation and wear resistance.

Full-carbide drill-countersink with optimized geometry and diamond coating (fig. 22), for rivet holes in composite materials, provides:

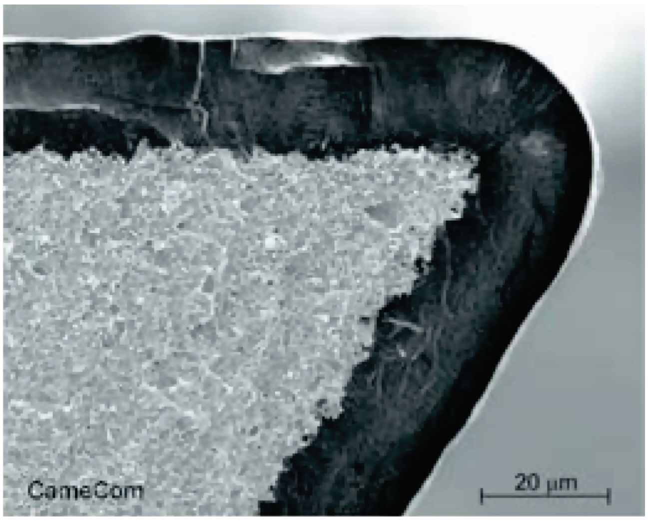


Fig. 21. Increased rounding of the cutting edge after diamond coating (CameCon)

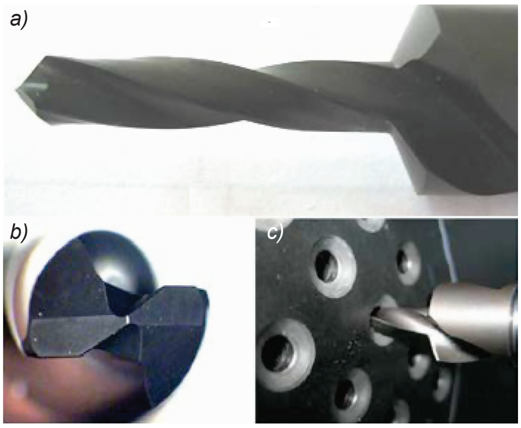


Fig. 22. Solid carbide countersink with a diamond coating: a) side view, b) front view, c) composite drilling (Mapal)

- very good quality of work surface,
- accuracy of hole diameter in class IT8,
- the use of double-feeds compared to classic drill bits,
- ten times longer life,
- possibility of dry treatment.

Despite the high unit price, diamond-tipped tools are increasingly used in high-performance machining operations in various industries. This is not only due to their very good cutting properties, which express the high quality of the shaped surfaces, the machining accuracy and the extremely long shelf lives, but also the technical and economic effectiveness of their use.

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