

Metal-bonded diamond tools - production and applications

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Although the early use of diamond as an engraving tool goes back to 350 BC, the modern application of diamond tools is about 140 years old. In 1862 the Swiss engineer J.R. Leschot conceived the idea of making diamond drill bits which soon found practical application. The first diamond circular saw blades for cutting stone were developed by F. Fromholt in France in 1885. The early blades used carbonados set around their periphery and were utilised to cut limestone and marble. Progress in the tool production routes, by making good use of powder metallurgy (PM) techniques, resulted in developing diamond grit impregnated saw blades which were put into operation around 1940.

Subsequent developments in the tool manufacturing technology may chiefly be attributed to the invention of synthetic diamond. Natural diamond has been used for centuries and efforts to manufacture synthetic crystals also date back at least several hundred years. They had remained fruitless until 1953, when positive and reproducible results were obtained by a team of researchers at ASEA. In 1955, quite independently and entirely without knowledge of what ASEA had been doing, General Electric announced its capability to manufacture synthetic diamonds on an industrial scale and was first to apply for a patent.

Permanent progress in the diamond manufacturing technologies fostered the commercial importance of synthetic grits, which is now accounting for over 95% of all industrial diamonds consumed. Over the past five decades, modern production techniques based on diamond tooling have been implemented into evolving areas of industrial activity enabling to do the job faster, more accurately and at less cost. They revolutionised machinery and processing techniques in the stone and construction industries, road repair, petroleum exploration, production of various parts and components made of ceramics, cutting frozen foods, etc.. The recent figures indicate that the demand for diamond abrasives reached an impressive volume of around 4.5 billion carats in 2010, as compared with approximately one billion carats in 2000 and 380 million carats in 1990. A broad classification of all diamond tools is given in Fig. 1.

In the new millennium the market for diamond tools continues to grow rapidly. Nowadays the marked decline in the price of industrial diamond makes it a commoditised product capable of competing, in terms of its price/performance ratio, with conventional abrasives such as silicon carbide and aluminium oxide.

Tool composition

For each specific application the chemical composition, particle size, shape and packing characteristics of the matrix powder as well as size, shape, strength and thermal stability of the diamond used for the manufacture of the tool all need careful selection if the required tool life and cutting performance is to be achieved.

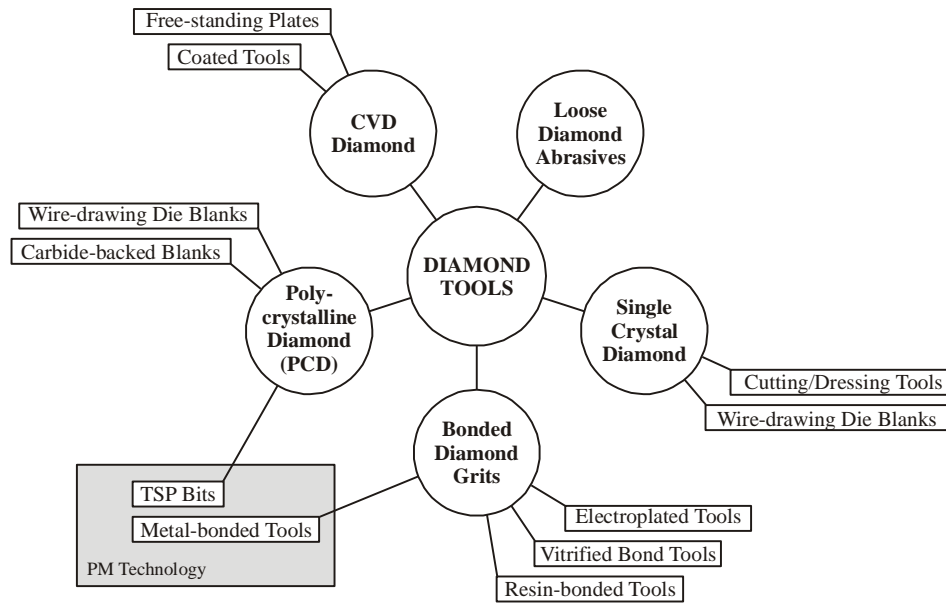


Fig. 1 Classification of diamond tools

The two basic functions of the metallic matrix are to hold the diamond tight and to wear at a rate compatible with the diamond loss. The wear resistance of the matrix has to correspond with the abrasiveness of the workpiece material, so that neither the diamond grits protrude insufficiently nor they are lost prematurely. When a hard and dense material is machined, very little debris is formed and only as a fine powder. Under such conditions the matrix wear is slow. On the other hand, when an open-textured and gritty material is machined at high processing rates, a great quantity of coarse debris is released which usually creates harsh wear conditions for the matrix.

The second and equally important function of the matrix is to hold the diamonds for as long as possible. The matrix capacity for retention of diamond grits is a complex, system dependent property which is affected by the material characteristics and application conditions as well. The most common matrices are composed of: cobalt, iron, nickel, copper, tin, tungsten and tungsten carbide. Except in mining bits, which are made by the infiltration process, very fine powders are readily used for the hot pressing and cold pressing/sintering routes.

Historically, cobalt has been the most valued matrix metal, especially in professional tools, due to superior mechanical characteristics and sintering behavior of its powders. As the average price of cobalt is highly unstable (Fig. 2) and increasingly contributes to the overall tool cost the recent trend within the diamond tool industry is towards replacement of cobalt-based tools with low cobalt or, preferably, cobalt free ones.

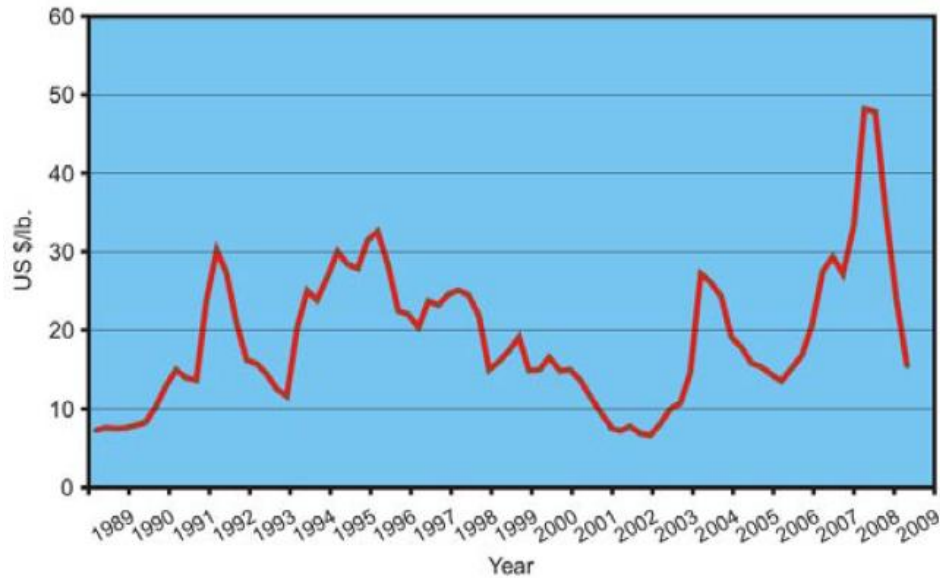


Fig. 2 The average quarterly Metal Bulletin free market price quotation for 99.8% cobalt cathodes

In the 1990's the price spikes of cobalt above 30 US\$/lb first raised the spectre of substitution. To date three families of fine copper-base and iron-base powders have been developed and launched commercially under the brand names: Cobalite (Umicore, Belgium), Next and Keen (Eurotungstene Poudres, France) to substitute cobalt powders in the manufacture of diamond impregnated tool components. These novel powders consist of a combination of at least two elements which have been co-precipitated in proprietary manufacturing processes to yield pre-alloyed agglomerates of sub-micrometer sized particles (Fig. 3).

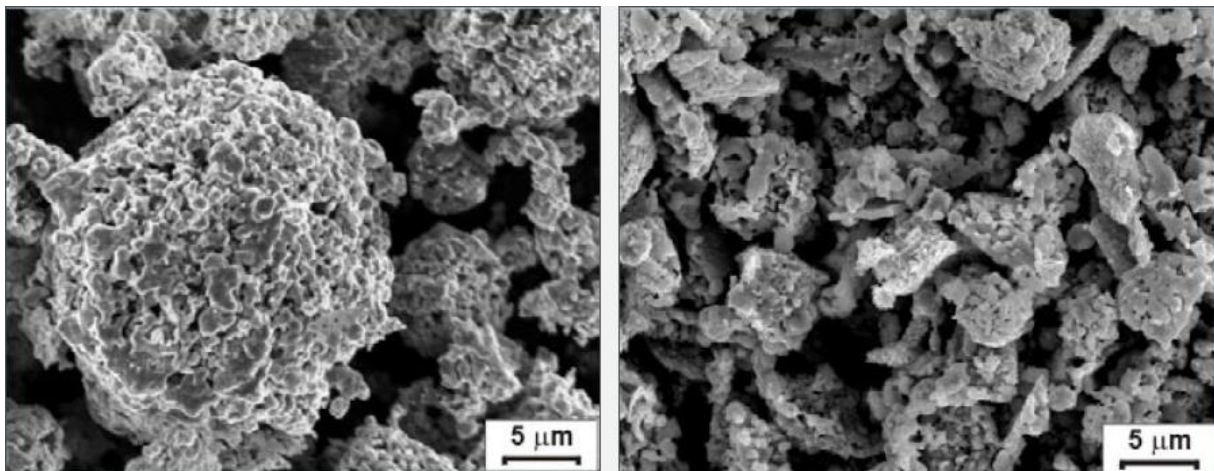


Fig. 3 Iron-base cobalt-free Cobalite CNF powder (left) and copper-base Next 200 powder (right)

As a rule fine, chemically alloyed powders exhibit excellent consolidation behaviour and yield hard and tough matrix but their manufacturing costs are high, compared to cobalt, and may account for around 80% of their selling price. Therefore it is common practice in the production of DIY and semi-

professional tools to utilise cheaper mixed powders usually based on a premix of carbonyl iron and atomized tin bronze. Inexpensive pre-alloyed powders obtained from low-priced raw materials by prolonged high-energy milling (mechanical alloying) are also being tested in an effort to further cut the matrix cost.

As regards the diamond abrasive, its type, size and concentration are factors that have the greatest significance. Diamond manufacturers provide the toolmakers with a wide range of natural and synthetic grits of varying properties such as mechanical strength, thermal stability and matrix retention characteristics (Fig. 4). The major difference between the natural and synthetic diamond is in the impurity content and particle shape. Natural grits, made by crushing mined diamond board, are free from metallic inclusions and hence show markedly higher thermal stability. They can retain strength throughout the whole range of PM processing temperatures, whereas synthetic grits begin to lose strength beyond 800°C. From the matrix retention viewpoint, crushed crystals possess excellent bonding characteristics, which result from the many re-entrant surfaces. This makes the natural diamond advantageous for certain applications, e.g. frame sawing of sedimentary and metamorphic stones. On the other hand, the irregular diamond surface impairs mechanical strength.

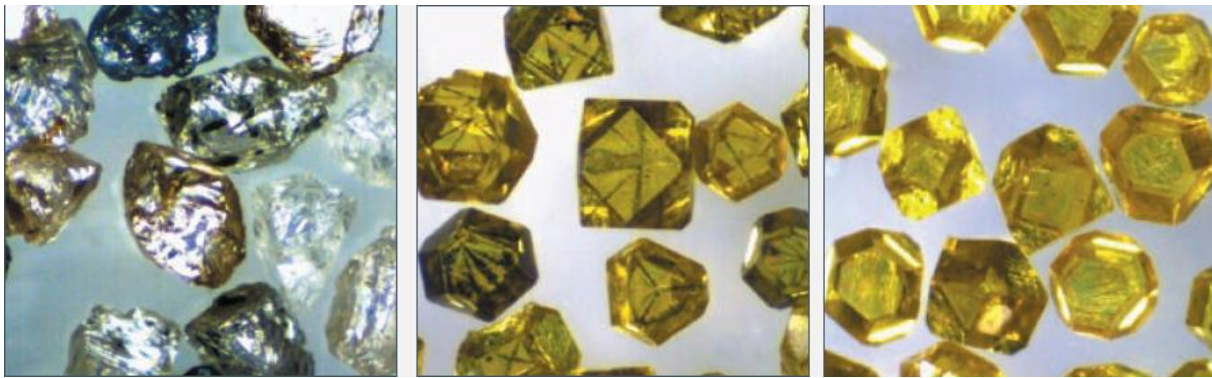


Fig. 4 Natural (left) and synthetic diamond abrasives produced by using cobalt-base (centre) and nickel-base catalyst (right)

The main advantage of using synthetic diamond is that it can be designed and manufactured to satisfy virtually any specific application requirements. By using either cobalt-base alloy or nickel-base alloy as a solvent in the diamond synthesis crystals of different internal structure and consequently of different particle properties can be obtained. The 'cobalt' grades are characterised by the presence of ordered arrays of metal inclusions within each particle and hence show a tendency to fracture in more irregular manner. This imparts free-cutting characteristics to the tool. In the 'nickel' grades the impurities are uniformly distributed throughout the particle, resulting in excellent cosmetic appearance and higher ability to retain mechanical strength after processing at elevated temperatures.

In addition to the internal structure, the particle shape will also affect the crystal breakdown characteristics. Diamonds that have smooth faces and a perfectly cubo-octahedral shape are stronger than irregular crystals. It is, however, not easy for the matrix to fully utilise such perfectly shaped crystals. Therefore the diamond itself has to co-operate with the matrix so as to minimise its excessive

pullout. The most effective way to improve diamond retention in the matrix leads through coating the crystals with a thin film of strong carbide former such as titanium, chromium or silicon (Fig. 5). An additional layer, of preferably nickel-base alloy, may optionally be applied with the intention to protect the carbide former from oxidation and to render the coating 'compatible' with the matrix material. Thus the enhanced diamond retention arises from the coating which chemically bonds to the diamond and forms a metallurgical attachment to the matrix on the outer side. The other benefits of coatings are: diamond protection from surface graphitisation, oxidation and attack by aggressive matrix components, and strengthening of flawed diamonds through 'healing' surface defects.

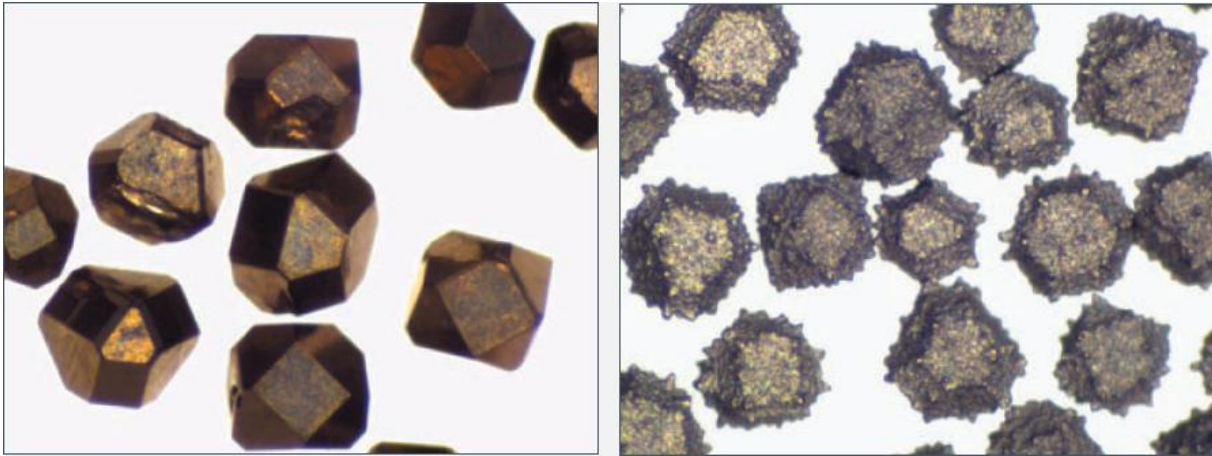


Fig. 5 Diamond abrasives coated with a single layer of titanium carbide (left) and an additional layer of nickel alloy (right)

The size of diamond particles determines their height of protrusion above the matrix surface and thus influences the clearance of swarf from the cutting zone. For efficient machining, there is a close relationship between the diamond size and the material being processed. There is a general tendency to apply grits coarser than 60 mesh for sawing and drilling; whereas the finer ones are recommended for secondary processing operations where perfect surface finish and edge definition are matters of primary concern.

In any brand of diamonds the finer grits, being relatively stronger, are chosen for machining harder materials; whereas the main advantage of using coarser grit is a bigger potential for faster material removal rate.

The diamond concentration, in conjunction with the diamond particle size, governs the number of cutting points per unit area of the working surface of a tool. The amount of diamond in the tool is based on a scale in which 100 concentration is equivalent to 4.4 ct per 1 cm³ (= 25 vol. %) of diamond impregnated layer. All other concentrations are proportional. Which concentration to use depends mainly on the diamond size, workpiece properties and machining conditions. In general, the more friable and abrasive the workpiece, the higher should be the diamond concentration.

Fabrication process

A typical fabrication process used in the manufacture of diamond impregnated segments and beads, utilises PM technology whereby a mixture of diamond grit and bonding powders is consolidated to form a cutting tool (Fig. 6). The hot pressing and cold pressing/sintering routes are most widely applied although other techniques, such as: hot isostatic pressing, infiltration, brazing and laser melting, may also be used.

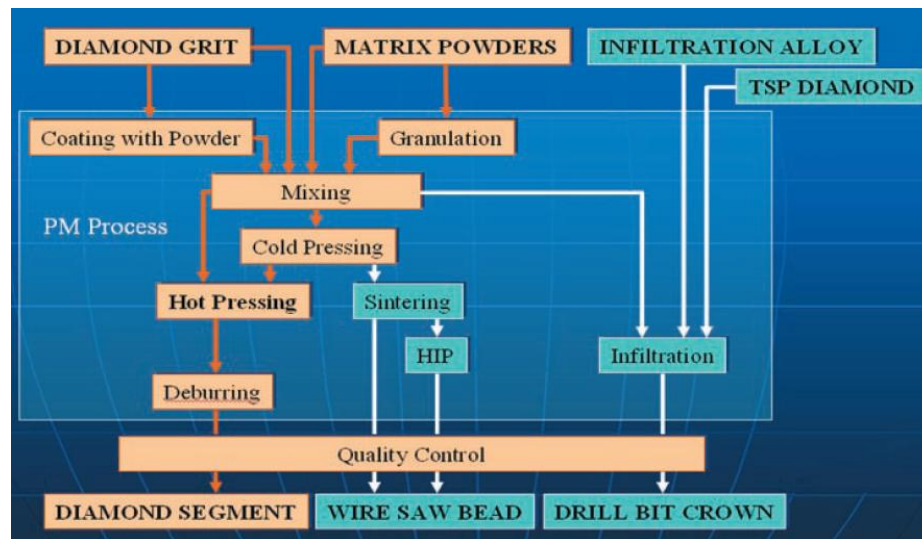


Fig. 6 Diamond tool production processes

The basic procedure consists of the following stages:

- matrix-diamond mix preparation,
- cold pressing,
- hot pressing or sintering,
- de-burring,
- quality control,
- finishing operations.

Matrix-diamond mix preparation

This process may comprise several steps. The most important is mixing of well selected metal-base powders in order to achieve the predetermined chemical composition, particle shape and size distribution. This operation is usually carried out in pendulum motion mixers. Binding agents and lubricants are added to the powder at this stage so as to reduce dust, prevent segregation and minimise wear of steel dies during subsequent cold pressing.

When the mixture is to be cold pressed by means of volumetric equipment the matrix powder has to be granulated to ensure required flow and packing characteristics. The diamonds may either be used in as-received condition or coated with a suitable powder prior to final mixing with the matrix powder.

Cold pressing

Cold pressing is an optional operation in the production of tool components having uniform structure but it becomes mandatory in the conventional cold pressing/sintering process or when multi-layer segments are manufactured by the hot pressing route. Among the variety of complex segment designs, two types have gained extensive application. First, if laser is to be used to weld the cutting layer to the steel support, the segments must have a diamond-free base possessing suitable fusion characteristics.

Second, so-called 'sandwich' segments have been found superior to the conventional ones in the circular sawing applications (Fig. 7). A typical 'sandwich' consists of three layers which differ in susceptibility to wear and hence a desirable saddle-shaped wear profile is being developed at work. This imparts a self-guiding characteristic to the saw blade and prevents it from deviating in the cut.

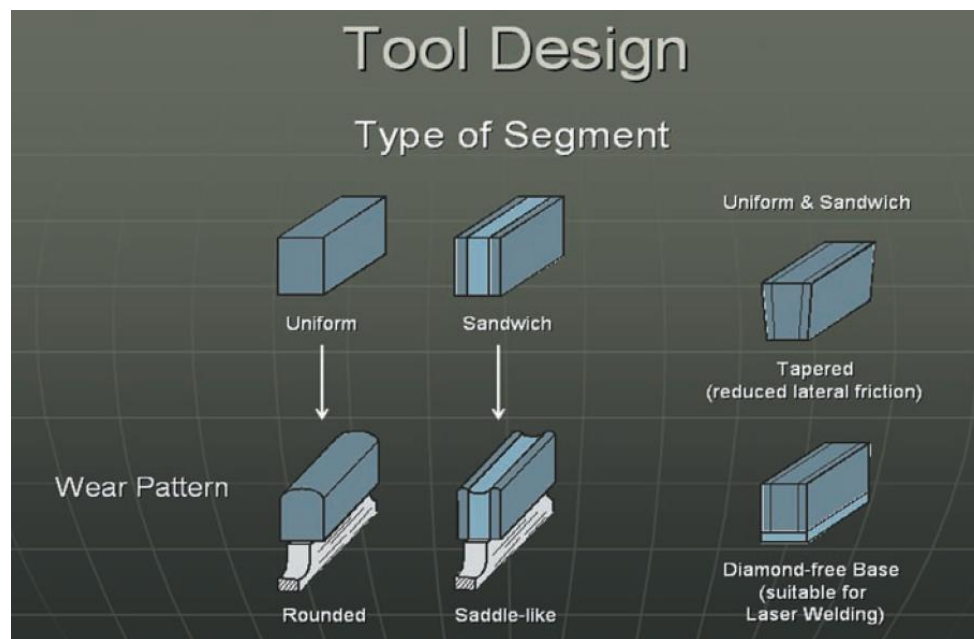


Fig. 7 Different types of diamond tool segments including: uniform (left), sandwich (centre) and combination of uniform and sandwich (right)

The cold pressing operations are performed in steel dies at low to medium pressures. There are two types of machinery used within the diamond tool industry. The conventional presses are fitted with vibratory powder dosing chutes and precision scales for the weighing of the correct amount of the mixture to fill the die; whereas the latest designs implement the volumetric filling principle. The gravimetric presses offer higher flexibility necessary to manufacture small quantities of segments. By contrast, despite higher investment costs, volumetric equipment is the preferred option for mass production of tool components due to its greater throughput, longer life and lower cost of pressing consumables.

Hot pressing

The hot pressing process consists of the simultaneous application of heat and pressure in order to obtain a product nearly free from internal porosity (Fig. 8). Compared to the conventional cold pressing/sintering PM route, hot pressing requires 2-3 minute hold at markedly lower temperature, but under a compressive stress, to reach higher density level.

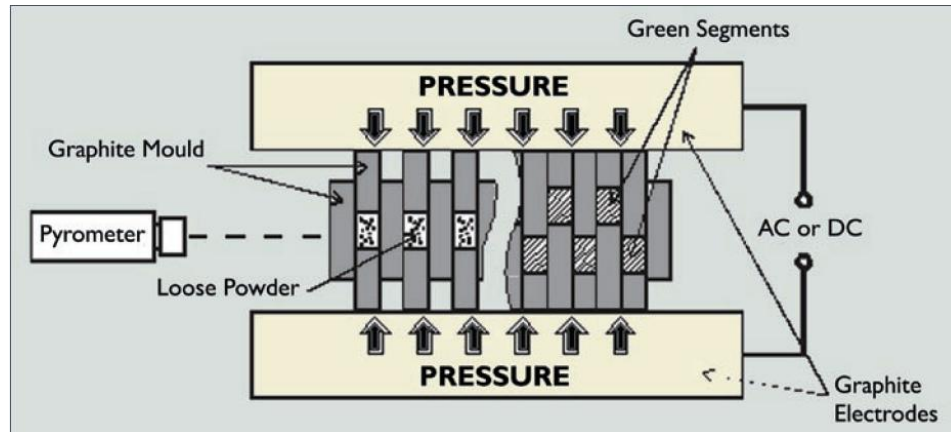


Fig. 8 Schematic representation of hot pressing

Hot pressing is normally accomplished using resistance heating equipment and either steel or graphite moulds. The latter, being in common use, offer higher production rates and, due to the formation of a CO/CO₂ reducing atmosphere at elevated temperatures, protect the powders against oxidation.

In the manufacture of certain continuous cutting layer/rim tools, the consolidation of the diamond impregnated layer takes place simultaneously with cementing it to the tool support.

Sintering

Sintering is an indispensable step in fabrication of numerous structural and tool PM components. Nonetheless, its application in the manufacture of diamond impregnated tools is limited by restrictions on the composition, mechanical strength and dimensional accuracy of the final product.

The conventional cold pressing/sintering route has, however, gain ground in the industrial-scale production of wire saw beads (Fig. 9). As opposed to hot pressing, cost savings and higher rates of production achieved by the use of furnace sintering outweigh, in this case, the shortcomings of this operation.

De-burring

Following the hot consolidation step the segments, or beads, often require cleaning and removing edge residuals. This is carried out during de-burring, which operation is usually performed by means of

grinding down the sharp edges on an abrasive paper or tumbling the segments with a conventional abrasive grit.



Fig. 9 Sintered beads and a wire saw used for sawing stone and concrete

Quality control

The quality control of diamond impregnated tool components is usually limited to a hardness test. The Rockwell B test is the most widespread technique due to its simplicity and inexpensiveness. A properly densified matrix-diamond mixture acquires a narrow hardness range. Incompletely densified material has insufficient toughness which results in its poor resistance to wear and diamond retention ability. Therefore, if there is any doubt about the hardness readings, the evaluation of density becomes another important quality check.

Finishing operations

When the PM processing has been completed, there is a need to attach the diamond impregnated products to a steel support to produce a tool. With the exception of wire saw beads, which are mechanically fixed on a steel carrier cable, either brazing or laser welding is used at this stage. Brazing is widely employed in the manufacture of saw blades, core drills and grinding tools for 'wet' applications and allows re-tipping of the steel support; whereas laser welding is mainly used in the production of small diameter, dry cutting circular blades in order to eliminate the possibility of segment detachment.

Further finishing operations consist in truing and dressing the tool to render its working layer concentric with the bore and, by exposing the diamonds, to allow efficient material removal from the outset.

During fabrication of circular saw blades, the steel core must eventually be subjected to an operation of nullifying lateral run-out and adding extra stress to stretch its centre section. This counteracts the centrifugal force tending to elongate the rim section of the rotating blade thus making it capable of spinning without wobble. Fig. 10 shows a selection of sintered diamond segments before attaching to circular blades and core drills.



Fig. 10 Selection of sintered diamond tool segments before attaching to blades and drill bits

Recent trends and developments

The recent tremendous price cuts on the diamond supply side and increased competition with low-cost labour countries has brought pressure on the leading edge of the industry to increase the rate of innovation and to carve a market niche for non-commodity products. In practical terms a great deal of effort is going into seeking novel segment compositions and grit distribution patterns to drastically improve the tool performance and lower machining costs.

Less power consumption and longer tool life are direct benefits from using coated diamonds but even more spectacular effects can be achieved by ensuring uniform distribution of diamond crystals in the tool. A technological breakthrough in manufacturing saw blade segments, wherein diamonds are equally-spaced and arrayed in a regular manner (Fig. 11), has been made but the grit setting procedures are a trade secret and this technology has not been implemented on a broader scale yet.

Applications

Diamond impregnated tools have proved to be instrumental in a wide variety of applications including extraction, sizing and final processing of natural stone, drilling and sawing of brickwork, concrete and

reinforced concrete, controlled demolition of buildings, road repair, machining of glass and ceramics, etc (Fig. 12).

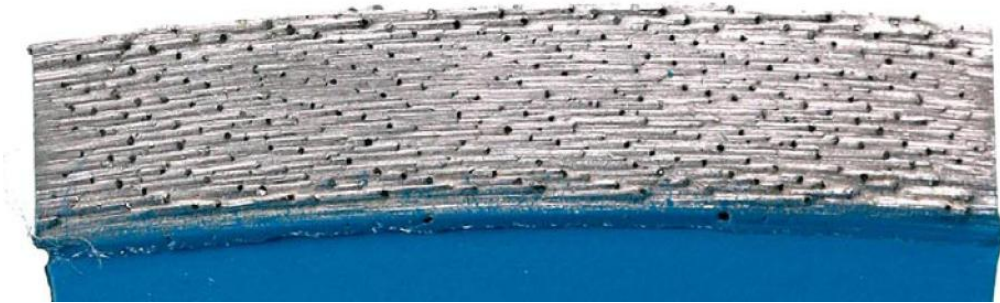


Fig. 11 Zenesis segment with arrayed diamonds (Courtesy of EHWA Diamond Ind. Co., Ltd.)



Fig. 12 Different types of diamond impregnated tools (Courtesy of EHWA Diamond Ind. Co., Ltd.)

The current trend is to diversify into applications still dominated by traditional abrasives with particular interest in developing linear blades for sawing granite as well as in applying diamond grits on a broader scale in the surface finishing operations.

Moving from the general to the more particular applications three case histories are presented to illustrate the present-day, highly sophisticated stone machining techniques. Even this limited number of examples furnishes a good idea of the immense versatility and cost-effectiveness of diamond impregnated tools.

Sawing granite on multi-blade machines for production of tiles

Architects and construction engineers have come to appreciate the high wear resistance and ease of maintenance of granite, as compared with marble and other natural stones, for flooring in public and private buildings. The growing demand for accurately sized granite tiles has long called for improvements on the traditional sawing technique using frame saws fitted with steel blades fed with steel shot abrasive. Over the past years, the growing application of fully automated, multi-blade sawing machines equipped with diamond saw blades has boosted productivity of granite strips. The other two bonuses are increased yield achieved with multi-blade sawing, due to the smaller kerf width produced by diamond saw blades, and much smaller space occupied by the machinery.

The so-called Scaletta system block cutter (Fig. 13) is a typical example of the multi-blade sawing equipment. The machine is run with two sets of 14 vertically mounted blades per set, which differ in blade diameter, and one horizontally mounted cut-off blade. To ensure smooth running of the system, each of the vertical blades has to be matched within narrow specifications in regards to ovality, balance, side run-out and tension, and fitted with sandwich type segments containing high-grade diamond grits embedded in a carefully selected metallic matrix.



*Fig. 13 Scaletta system multi-blade saw cutting a granite block
(Courtesy of EHWA Diamond Ind. Co., Ltd.)*

The first set of blades, having the smaller diameter, cuts to half of the strip width, whereas the bigger blades complete the cut. Typically, blades having diameters from 800/1200mm to 1000/1600mm are used to cut granite blocks into strips which are further calibrated, polished, sized and chamfered to yield tiles in square sizes from 400mm to 600mm.

Blocks are cut at a traverse speed of between 14 and 18m/min and a depth of cut ranging from 0.5 to 1mm depending on the workpiece sawability. The rotational speed of the spindle depends on the applied saw blade sizes and is adjusted to achieve the peripheral speeds of around 24 and 38 m/s for the smaller and bigger saw blades, respectively.

Contouring natural stone slab edges with profiled milling cutters.

The recent technological innovation has led to an enormous increase in the production of natural stone components used for interior decoration, such as kitchen worktops, tabletops, side panels for built-in furniture, staircase treads, window sills, door frames, and many other fittings which are normally made of wood. With this type of production many different profile and edge finishes are required. They can economically be accomplished on numerically controlled contouring machines, fitted with a wide range of diamond tooling to cover all these possibilities.

The latest generation of contouring CNC machines can handle very large stone slabs offering the tool travelling distance of 3500x2000mm (Fig. 14). Equipped with large tool stores, inclinable spindles, laser tool travel controls, touch probes to measure the workpiece dimensions, flat and convex circular saw blades for rectilinear and curvilinear cuts respectively, as well as user-friendly programming facilities, these machines enable the most complicated stone-shaping operations to be carried out unattended.



Fig. 14 NC260 Contourbreton machine (Courtesy of Breton S.p.A, Italy)

Wire sawing of stone and concrete

Over the past three decades, diamond wire sawing technology has made significant inroads into the stone and construction industries, primarily for quarrying of stone blocks and their further division, for construction, renovation and demolition of concrete structures, and recently in the stoneyards, where single-wire and multi-wire stationary machines are increasingly used for block slabbing and profiling of stone slabs. Examples are given in Figs. 15-17.



Fig. 15 Cutting a large block from the rock face (Courtesy of EHWA Diamond Ind. Co., Ltd.)



Fig. 16 Portable wire machine making a vertical cut in a concrete wall (Courtesy of Hilti Corp).



Fig. 17 Multi-wire machines are increasingly used for sawing thick sedimentary and metamorphic stone slabs, and as an alternative to the traditional steel shot gang saws used for granite block slabbing (Courtesy of Co.fi.plast. Srl).

There are at least two advantages to block extraction by the diamond impregnated wire that have made this technique attractive to stone quarries. First, it offers markedly higher production rates and is not so labour-intensive as flame burning, blasting and other conventional methods used to open the rock face. And second, it minimises waste in any case and dramatically increase output of blocks usable for monumental purposes in areas where flawed or fragile stone is quarried.

The typical cutting rates range from 2-4 m²/hour on granite up to 8-9 m²/hour on travertine and other easy-to-cut types of stone, with the wire linear speed similar to circular sawing.

The versatility and economic advantages of the wire saw technology have also been recognised in the construction industry, where portable wire saw machines are used for controlled demolition, construction and renovation purposes. The ability of the diamond impregnated wire to cut cleanly, quickly and accurately, with little noise and vibration, makes this tool an ideal alternative to blasting or jack hammering with flame cutting of the rebar, which were previously used in removal of thick sections of reinforced concrete or brickwork. The cutting rates achievable on various construction materials vary widely from 1-6 m²/hour on reinforced concrete, through 5-11 m²/hour on plain concrete, up to 10-18 m²/hour on masonry depending on the type of concrete aggregates, percentage of steel reinforcing and brick composition.