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DIAMOND APPLICATIONS IN THE OIL INDUSTRY

by

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SUMMARY

Diamond bits have allowed the oil industry to develop previously unaccessible fields. An overview of the main diamond features shows why diamond is so performing for rock cutting in oil drilling. The advantages and limitations of the different diamond types, both natural and synthetic are explained with reference to drilling applications and with special emphasis on polycrystalline PDC (Diapax) and TSD (Tripax, Syndax) products.

RESUME

Lors des dix dernières années, les outils diamantés polycristallins ont réalisé une percée. Un aperçu des principales propriétés du diamant explique les raisons de ce succès. Les avantages et les limitations de chaque type de diamant, utilisé dans les outils diamantés, permettent de mieux guider les foreurs dans le choix d'un outil plus performant. L'importance des produits synthétiques polycristallins PDC (Diapax) et TSD (Tripax, Syndax) est soulignée.

KEY WORDS

Diamonds, drilling, properties, polycrystalline.

MOTS CLE

Diamant, forage, propriétés, polycristal.

1. INTRODUCTION

Diamonds, both natural and synthetic, have a wide range of applications in industry. Two essential properties of diamond determine its efficient usage as an abrasive: hardness and thermal conductivity. Even where diamond is not the best agent for destruction of other materials, it still can be preferred because of the longer lifetime of the diamond too, its shorter working time or the quality of the cut.

In the oil industry the diamond drilling bit using polycrystalline diamonds has been established since ten years. The oilfield drilling industry was at that time strongly dominated by the tricone roller bit, introduced by Hughes in 1933, and reaching a share of 98 % of the world market in meters drilled. Nowadays oilfields which are highly sensitive to technological innovations such as the North Sea, have largeley shifted to polycristalline diamond bits which already stand for 60 % of the meters drilled.

PDC tools contain a thin layer of synthetic polycristalline diamond which is agglomerated under a high pressure and temperature regime with a cobalt - type catalyser. This layer is supported by a tungsten carbide substrate. Recently thermostable diamonds have practically replaced natural diamonds in the market for hard, abrasive formation drill-

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[1] DB Stratabit S.A., Avenue du Pont de Luttre 74 - B-1190 Bruxelles (now part of NL-Baroid).

[2] paper based on communication presented at Diamond Symposium, Antwerp, 24.11.1989.

ing. This diamond type has a better shock resistance and it preserves its cutting profile.

The most important advantage of the polycrystalline diamond is its self - sharpening capacity, resulting in a continuously efficient tool. Average drilling performances of 2000 m to 3000 m per bit can be expected for rates of penetration of 30 m per hour.

The rentability of the North Sea oilfield is largely due to the development of the PDC tool. An average well was drilled ten years ago in 90 days, using classical technologies. Today the same well will be drilled in 35 days, sometimes even in 15 days. Technological development of polycrystalline or thermostable diamond tools is continuing, it will lead to further improvement of drilling and coring performances.

2. DIAMOND PROPERTIES

2.1. OUTSTANDING FEATURES

Hardness:

Diamond is the hardest material as compared to natural and composite materials. The closer materials being the CBN (synthetic material) and boron carbide, titanium ans silicium carbides, it is in this respect the most suited to destroy rocks.

Rock Type	Speed (m/s)	Water	Mud	Diesel	Air
Marble	1	0,20	0,17	0,34	0,33
	5	0,15	0,11	0,13	0,15
Sandstone	1	0,03	0,04	0,05	0,10
	5	0,05	0,04	0,30	0,30
Granite	1	0,09	-	-	0,18
	5	0,05	-	-	0,14
Shale	1	0,09	-	-	0,18
	5	0,06	-	-	0,15

Table 1: Measured PDC friction coefficients.

Hardness: ranging from 5700 kg/mm^2 to 10400 kg/mm^2 according to the pureness. This feature is actually difficult to measure accurately. Average value: ±8000 kg/mm^2

By comparison:

Tungsten carbide: ±1880 kg/mm^2 i.e. 3 to 6 times less.
Steel: ±800 kg/mm^2

The resistance of abrasion is in a matter of fact related to the hardness itself. It is because the diamond is the best abrasive that its first application in drilling bits was in impregnated bits working by abrading action.

If we attempt to plot an idealized curve of resistance to abrasion vs impureness (Fig. 1). As it will be shown later, this property is not always in line with the impact resistance. As far as PCD's (polycrystalline diamond) are concerned, this resistance is also conditional upon monocrystal bonds. Their initial grain size governs the bond strength (see Diapax description - § 2.2.2.1), whereas the metallical agent cobalt decreases it.

It should be noted, however, that, due to different modes of wear between natural diamond and PCD, it is very hard to sort them by abrasion resistance.

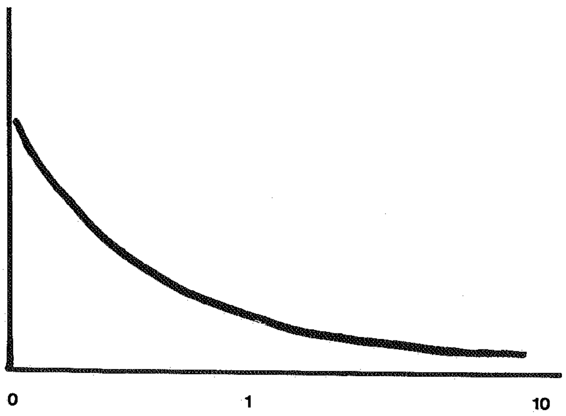

Figure 1: Abrasion resistance versus impurities content in diamond (horizontal scale % of impurities; vertical scale : abrasion resistance).

Compressive strength: diamond is also among the most compressive resistant materials.

Diamond = 500 T/cm^2.
Tungsten carbide = 297 T/cm^2
Steel = 71 T/cm^2

Friction coefficient: very low, but function of cutter speed, mud type and formation in drilling bits (Table 1). This is a highly valuable feature as working diamonds are constantly "scratching" the formation ; which could generate a lot of heat if the friction coefficient was not that low.

Thermal conductivity: from 9 to 26 watt/degree at room temperature (20°C). The highest conductive material, 2 to 7 times copper and 14 times Tungsten carbide (which already is not a bad conductor). This is another important property as it governs the dissipation of the calories generated by the working action of the diamond. This heat transfer is almost instantaneous across the mass of the diamonds, which leads to a uniform bulk temperature except on its working surfaces. This outstanding property will be later emphasized by the illustration of the high sensitivity of the diamond to high temperatures.

Density:

Diamond: 3,52 g/cm^2
Tungsten carbide: 15,63 g/cm^2
Steel: 7,85 g/cm^2

Melting point:

Diamond: 3650°C
Tungsten carbide: 2860°C
Steel: 1530°C

2.2. PROPERTIES LIMITING DIAMOND USE

2.2.1. Chemical properties

Diamonds are chemically inert to acids or any other chemicals except at high temperature and sometimes in certain environments.

2.2.1.1.Oxydation

Starting at a determined temperature level and in oxidizing atmosphere. This is statistically the more frequent way of destruction of the diamond. In the presence of O_2, carbon which is the component element of diamond starts burning around 550°C releasing CO_2-CO. So, the maximum allowable temperature should be fixed at 650°C in oxidizing atmosphere. Of course, diamond will not become oxidized at higher temperature in neutral or reducing atmosphere.

Precautions to be taken:

a. During manufacturing process

Mixed powder should be treated and checked for the presence of O_2. Fortunately, the presence of W, tungsten carbide and graphite significantly reduces the oxidization rate. Furthermore, infiltration takes place under protective atmosphere.

b. At use

Faster wear rates should be expected working with cooling media such as air, foam, aerated muds. Oil base mud is also critical when using diamond due to a lower rate of cooling. It is not recommended to use OBM (Oil-based-mud) in hard formation where high temperatures can be reached at the diamond edge.

In fact, temperatures as high as 400°C have been registered close to the cutting edge of PCD's at optimum cooling rate (Fig. 2). Much higher temperatures should be expected at the very cutting point in less favorable conditions.

2.2.1.2. Graphitization

Let us remember that, if we only consider the basic and final products of the graphitization reaction, this is nothing else but the reverse reaction of the diamond synthesis.

If we consider the two phases (graphite - diamond) equilibrium diagram of the diamond (Fig. 3), we notice that diamond is unstable at normal ambient conditions and more even at working ones. Nevertheless, as reaction is rate is infinitesimal, it would take thousands of years to the diamond to be converted back into its more stable phase. But, under certain physico-chemical conditions, this rate can be highly accelerated:

1. Only under heat input conditions, reaching high temperature levels, this reaction can be instantaneous. For example, a diamond gem can withstand a temperature as high as 1600°C in inert atmosphere but this graphitization temperature level decreases along with the

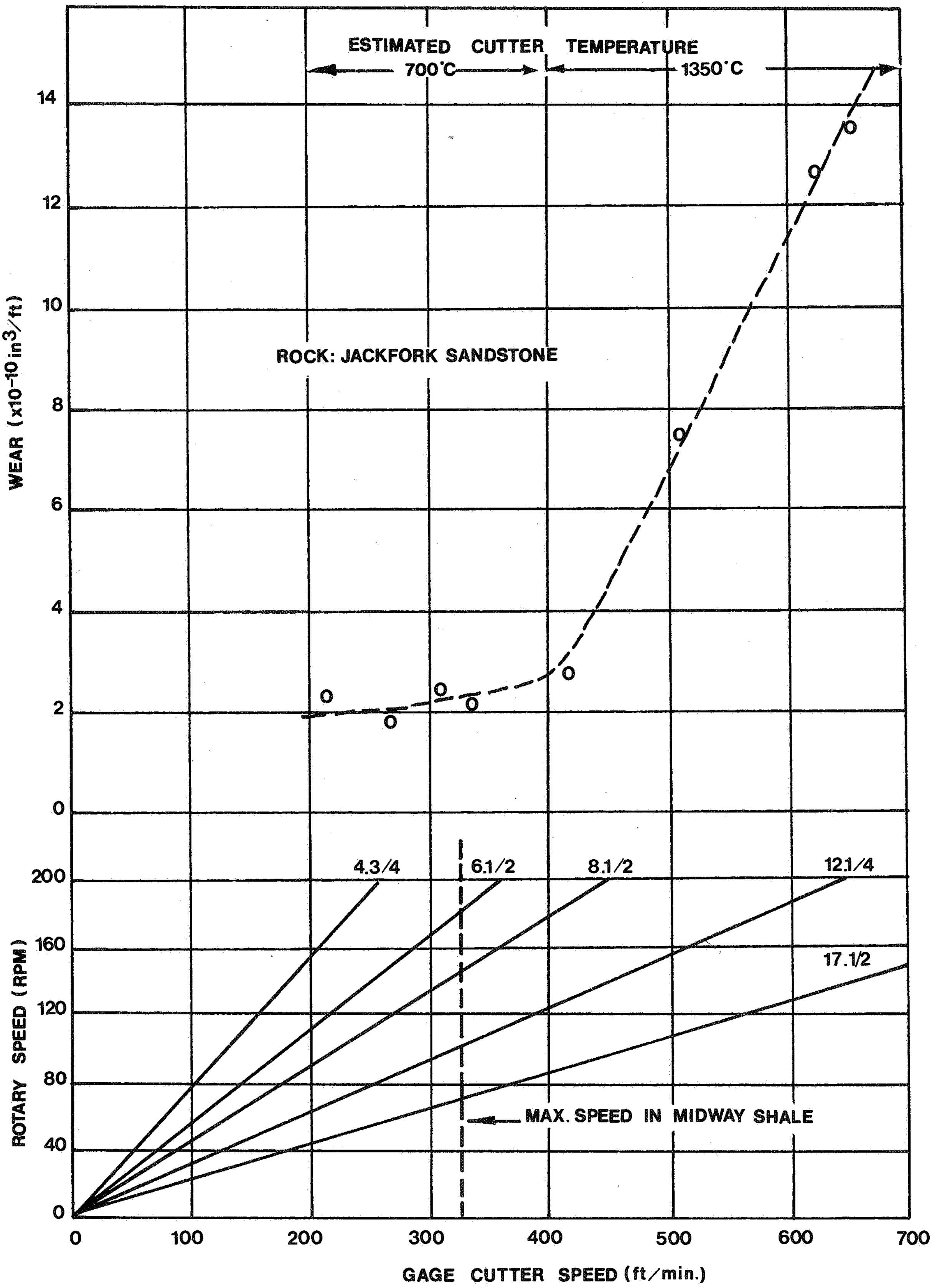

Figure 2: Estimated temperatures at cutting edge of PCD's, showing the limitation of PDC usage versus peripherical speed.

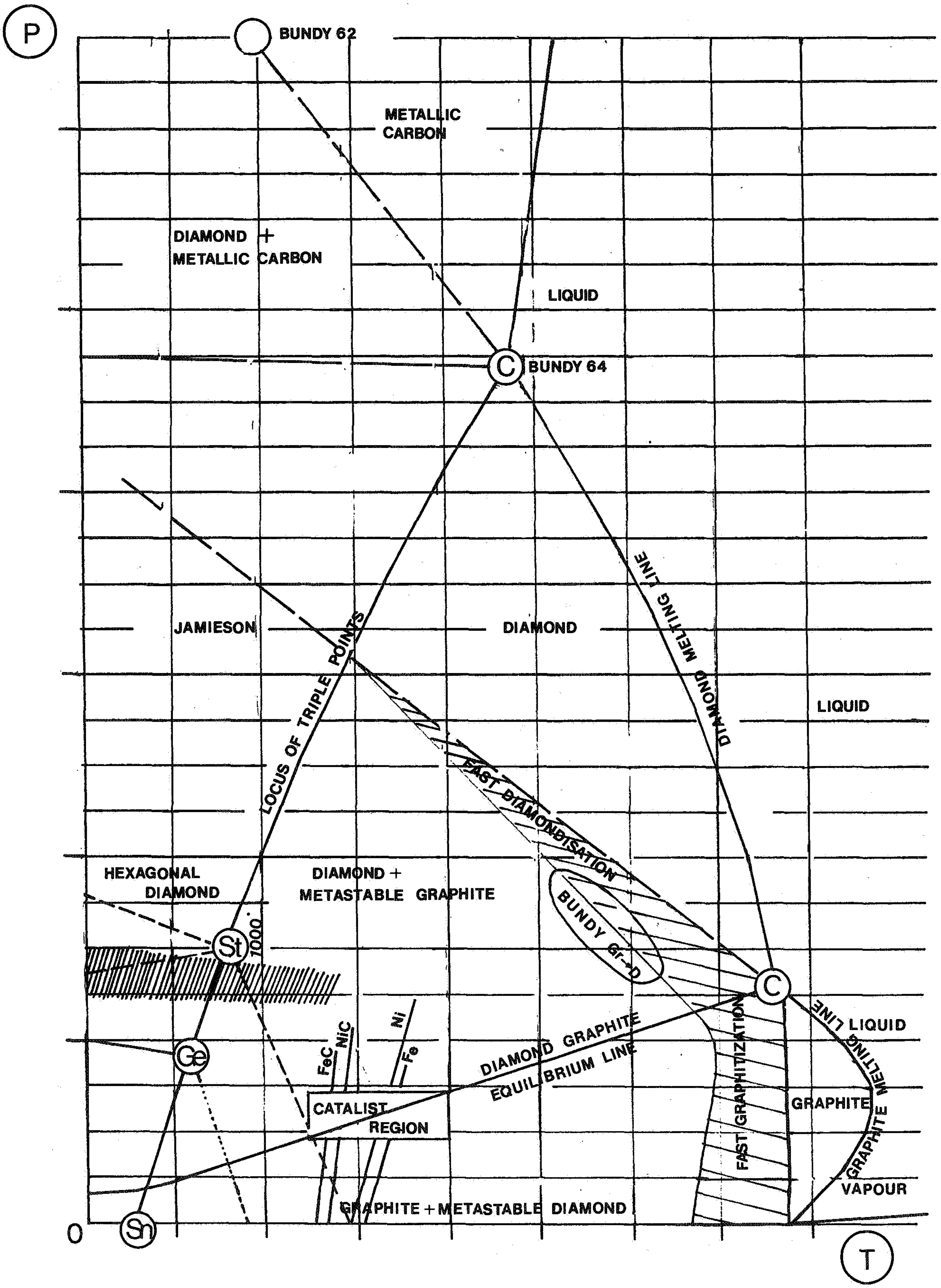

Figure 3: Phase diagram for carbon (horizontal scale: temperature, 500°C temperature increase per subdivision; vertical scale: pressure, 100 bar pressure increase per subdivision).

impurities content of the diamond. Graphitization could either take place at the surface of the stone, giving rise to a self destructive graphite layer or, due to the high conductivity coefficient, deeper into the stones, in which case it will burst due to the larger crystallographical mesh of the graphite.

2. Through the additional input of catalysts, this destructive process is becoming more crucial because it occurs at temperatures much closer to actual working conditions. The more common catalysts are: W, Ti, Co, Cr, Ni, Fe and Mn. The last two ones graphitize diamond at the lowest levels of temperature: iron from 700 to 750°C and manganese a little bit below 1000°C while others only start graphitizing above 1000°C.

The synthetic diamond is produced by using catalysts to reduce the needed temperature to synthetize the diamond. The most common catalysts used are Fe, Ni, Co, Cr. The parameters used in the synthesis are 55 Kbar pressure and 1400°C (Fig. 3). But it is to remember that the reverse catalization from diamond to graphite can be achieved at faster rate and lower temperature when drilling or coring formations, containing catalyst metals. This is due to the fact that high pressure does not exist in cutting action but a minimum temperature has to be achieved for that process it is in the range of 700 to 800°C and it is function of the type of catalyser.

Precautions:

a. Binding agents and manufacture temperatures should be carefully selected

Examples:

1. When using iron for sintering process at 900 - 950°C, diamond vanishes after 1/2 hour through complete graphitization.
2. Infiltration times are accurately monitored when using iron or manganese hard alloy.

b. At use:

Elements such as Fe and Mn could graphitize diamond but to different extents according to the ore type hosting these elements.

Examples:

FeS_2 (pyrite) can destroy the diamond in a streak a few decimeters long as the layer of FeC which starts forming above 700°C is constantly replaced due to its own very weak wear resistance and diamond being reexposed.

On the other hand, other iron oxydes such as hematite and ilmenite used as weighing agents have not proved to be so detrimental. It should, however, be noticed that, according to their origin, their properties may vary considerably.

So, for every possible graphitizing agent (oxyde, sulfide, etc.), its stability diagram should be examined to check if carbides of the same element could not be more stable at working conditions.

Definitively no attempt should be made to drill junk, packer left in the hole etc.

2.2.2. Mechanical properties

Due to its cleavage planes, diamond will eventually wear along these through a microchipping process which is enhanced by combined effects of shocks and high friction.

In spite of its highest compressive strength, it could however be exceeded on those very spots where the load is more heavily concentrated due to the heterogeneous pressure distribution on the bit profile.

The impact resistance is generally rather poor as a result of the presence of cleavage planes. It is conditional upon:

1. Diamond size: as larger stones are more likely to contain higher concentrations of impurities, their impact resistance is lower. Hence the big advantage of microcrystals over larger stones in all diamond application industries.
2. Diamond types: impurities distribution is a major factor (Fig. 4).

In the oil drilling business, polycrystalline diamond agglomerates are manufactured from synthetic monocrystals with precise proportioning of impurities in order to reach the highest possible impact resistance. In other sectors such as mechanical engineering where resin diamonds are used, more brittle diamonds are preferred for their self-sharpening properties.

Precautions

a. From manufacturer:

Eliminate diamond which will not withstand heavy shocks through a two stage treatment for natural type diamond:

- mechanical rounding to eliminate cracks and other surface defects.
- chemical polishing to eliminate all the diamonds with high internal stress levels.

For synthetic mateirals, such as polycrystalline diamonds, back up material is an important factor to be considered.

b. From user:

The operator should avoid creating unnecessary shocks through improved operating practices. Downhole motors have also proved to generate less shocks.

2.3. OTHER PROPERTIES

2.3.1. Shape

The shape has an important influence on the cutting action of the diamond and hence on its performances. The development of bits set with diamond working in a shearing mode has long been impaired by the unaffordable price of West African quality and other limitations of cube stones but, for the last few years, has undergone a fast growing rate with the advent of PDC materials. PDC bits represent now more than 70 % of the total production of DB Stratabit.

2.3.2. Granulometry

Basic key rule: the higher the rock hardness and the linear cutting speed, the smaller should be teh stones in order to be able to reach the required loading on the rock (Fig. 5).

3. DIAMOND TYPOLOGY

3.1. NATURAL DIAMOND

3.1.1. Boart

Etymologically, this South African word came from "bastard" because, being a waste material, this grade was unfit for any jewelry application.

3.1.1.1. Rough Boart: The must stones are extracted from "Congo" mines which altogether contain less as 10 % jewels. The rough Boart stones are agglomerates of very impure crystals which cannot be used as extracts due to their unsuitable shape and the poorly linked crystals. They have to undergo various treatments, starting with crushing into smaller grains in equiaxial shape with sharp and brittle edges. This quality is alled "ST" after sifting the grains according to their grit size. They are only use when economical efficiency is not required. They can be used in impregnated bits for low cost products (Pl. 1, photo 1).

3.1.1.2. Non crushed Boart: Along with the rough Boart, another 2 % of cube Congo stones is mined as well as 8 % of round ones. These can be used on condition of a previous visual inspection. The Congo Round is also called ***Hard Core***. This designation comes from the fact that they contain a very hard central core surrounded by a rather weak gangue. The cores are very close to jewels; this explains why natives used to extract them for the jewelry. Owing to its rather porous outer skin with high impurities content, the non processed Hard Core has low compressive strenght and resistance to abrasion. So, it should be treated the same way as crushed boart.

The cube boart is available in sizes ranging from 1 to 4 stc (stones per carat); as we do not want to lose its sharp edges, we cannot process it. They pass a visual selection but there is also a natural selection based on the infiltration process as stones under high levels of internal stresses and with internal defects are likely to burst at this later stage. If, during the visual inspection, the cube stones are discarded or, after salvaging the bits, they present the slightest defects, they will be further processed as rough boarts. Their salvage value is normally very low because, showing only one broken edge, they can no longer be considered as cubes due to their bad retention by matrix in that condition.

3.1.1.3. Diamond processed from "ST" or "HC" grades: Further treatments will only lead to rounded shapes suitable to the "plowing" mode of destructive action:

Mechanical rounding:

Rubbing against each other in the presence of some bigger "WC" beads, most stones are rounded except the already cracked ones which will break apart and be eliminated from further treatment. This will lead to a diamond weight loss ranging from 20 to 30 % at this stage. This operation, apart from reducing considerably the size of the diamond, will particularly improve the shock and compressive strengths (sphere shaping) but to a lower extent the abrasion resistance except for the HC where the brittle gangue is replaced by a tougher outer skin.

This mechanical treatment is followed by another visiaul selection to discard the cracked grains. The obtained quality is designated "EX".

Chemical polishing

This process cannot be divulgated but, roughly speaking, is a blend of high thermal shock at <900°C similar to quenching, and superficial oxidization. Up to an additional 10 % will burst during this operation. It also yields an excellent surface finish with purposely left tiny surface cracks which help in cooling through a better surface irrigation. So this treatment, apart from further eliminating weak crystals, will reduce the friction coefficient and increase its wear resistance. So this grade that we designate by "SP" (which is often mistaken for hard core) has obviously less bite than other grades but other outstanding qualities which make this "premium" our standard grade as it is the best suited to all formation compressive strengths and a wide range of abrasiveness (Pl. 1, photo 2).

The commercial denomination "hard core" is in fact a chemically polished Congo round, it is the highest quality of Boart type material.

Final visual inspection and sorting by grit size.

The diamond wear during drilling is a further step into the refining process. So, diamond which has already been salvaged and further processed should not be considered as lower quality diamonds if a proper preselection is made.

The natural diamond described here is now only used for extremely hard formations and for gage protection or surface protection in special type bits. This diamond was representing 90 % of the diamonds used in the past before synthetic diamonds came on the market (PCD and TSD). It is now representing less than 5 % of the diamonds used in oil and gas drilling.

3.1.2. Drilling ("J" designation in DB)

As the name states, this quality is essentially used for mining and oil drilling bits. These are more commonly known under West African quality although the biggest supplier is currently South Africa. The remaining part is produced in Ghana, Liberia and Guinea. They are mined along with more than 60 % of jewelry gems.

Selection: as their performances depend to a large extent on the features of each particular batch, the grading of their impureness content is of prime importance (our lower quality is designed "JB"). Afterwards, they are graded according to their grit size (up to 100 mesh).

Properties: these diamonds have undergone a very pronounced degree of crystallisation up to dodecahedral and even octahedral shapes. Their crystallographical structure is much sounder and they have no gage. To their higher pureness is related a higher abrasion resistance. Because of their sharp edges, they have a higher cutting speed but also greater sensitivity to shocks (they should no be used in fracturated formation due to their crystal breakage risk) (Pl. 1, photo 3);

Drawbacks: their economical feasibility should be carefully studied prior to any use (for example, through the break even curve): this is due to their high cost which can mount to ten times more than "SP" quality's according to their pureness and shape (octahedral are even more expensive !).

Further processing: only the "casting", which is an equivalent to the "JB" but in lower grain sizes, is processed due to its low tendency to graphitization occurring during sintering: it is used in our impregnated blades and back-ups. Also for their lower sensitivity to graphitization, West African diamonds of the highest quality are often preferred to synthetic ones in the smaller grain size range used in the oil drilling.

These high quality diamonds are now only used when very abrasive formations are encountered and, at that time, it is really necessary to make a preliminary economical valuation.

3.1.3. Carbonado

This variety was the first one used in the petroleum industry and is still at present the only available natural polycrystalline diamond. In fact, they are polycrystal agglomerates with silicates. Due to its light porosity and varying silicates content, its properties are very uncertain: it can be harder than a Hard Core but also more friable than a sugar lump. In addition, it is completely opaque and irregular in shape, which makes it very difficult to set on a bit. Also, as its high price cannot be justified by better performance, we discontinued its use a long time ago.

3.1.4. Ballas

This type of diamond is spherical. The production is very low and mainly comes from Brazil. It is a polycrystalline material (very small crystals) agglomerated radially. The main characteristic of this diamond is its high abrasion resistance.

3.2. SYNTHETIC DIAMOND

The discovery of this process in 1955 has been a major breakthrough in the diamond industry but it was not before the late seventies that the advent of synthetic polycrystalline materials could revolutionize the oil drilling applications (Lorent, this volume).

The reason for such a huge success is the possibility to produce diamonds exactly like the industry requires them. Synthetic diamonds are tailor-made for each application. Therefore, they are more convenient than the natural corresponding products.

3.2.1. Monocrystal

Synthesis process

Monocrystals are obtained by inserting in a ceramic cell several layers of graphite into layers of catalysts such as Fe, Mn, Ni, Co, Cr (in the earlier times, it used to be Fe). Those cells are then brought through a complex temperature and pressure cycle to 1400-1450°C and 55 Kbar. The metallic elements melts and dissolve part of the graphite in order to form metastable carbides from which diamond starts crystallizing (Lorent, this volume).

Most of the synthetic crystals are yellow or green. This is due to the catalyser content (Co for yellow, Fe for green).

The impurities content may vary from 0.1 % up to several %; the best grits used for oil drilling applications are the purer varieties as these are less brittle; they still contain a much higher proportion of catalyser than natural, which results in better shock resistance (Fig. 4).

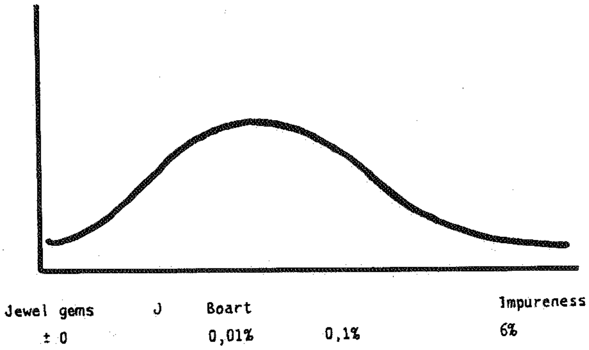

Figure 4: Shock resistance versus impurities concentration (horizontal scale left: natural diamonds; right: synthetic diamond grids; vertical scale: shock resistance).

Limitations

At present, as available presses can not economically withstand those high pressures longer than 45' to 1 h, the growth of the crystals is limited to a size of 25-30 mesh (<7 mm). In order to get stones twice as big as those, we would in fact require from 4 to 5 hours under these same conditions; this is due to the cubic exponential growth of the crystals. This is why, until polycrystalline diamonds came on the market, there was no application for synthetic diamonds in the oil industry. Actually, some large size jewelry cristals are produced. We cannot expect that such types of crystal are produced for industrial application unless drastic cost reductions in their production could be accomplished.

3.2.2. Polycrystallines

3.2.2.1. Manufacturing process

Progress in synthetizing diamonds gave birth to new technological uses for the diamond composites.

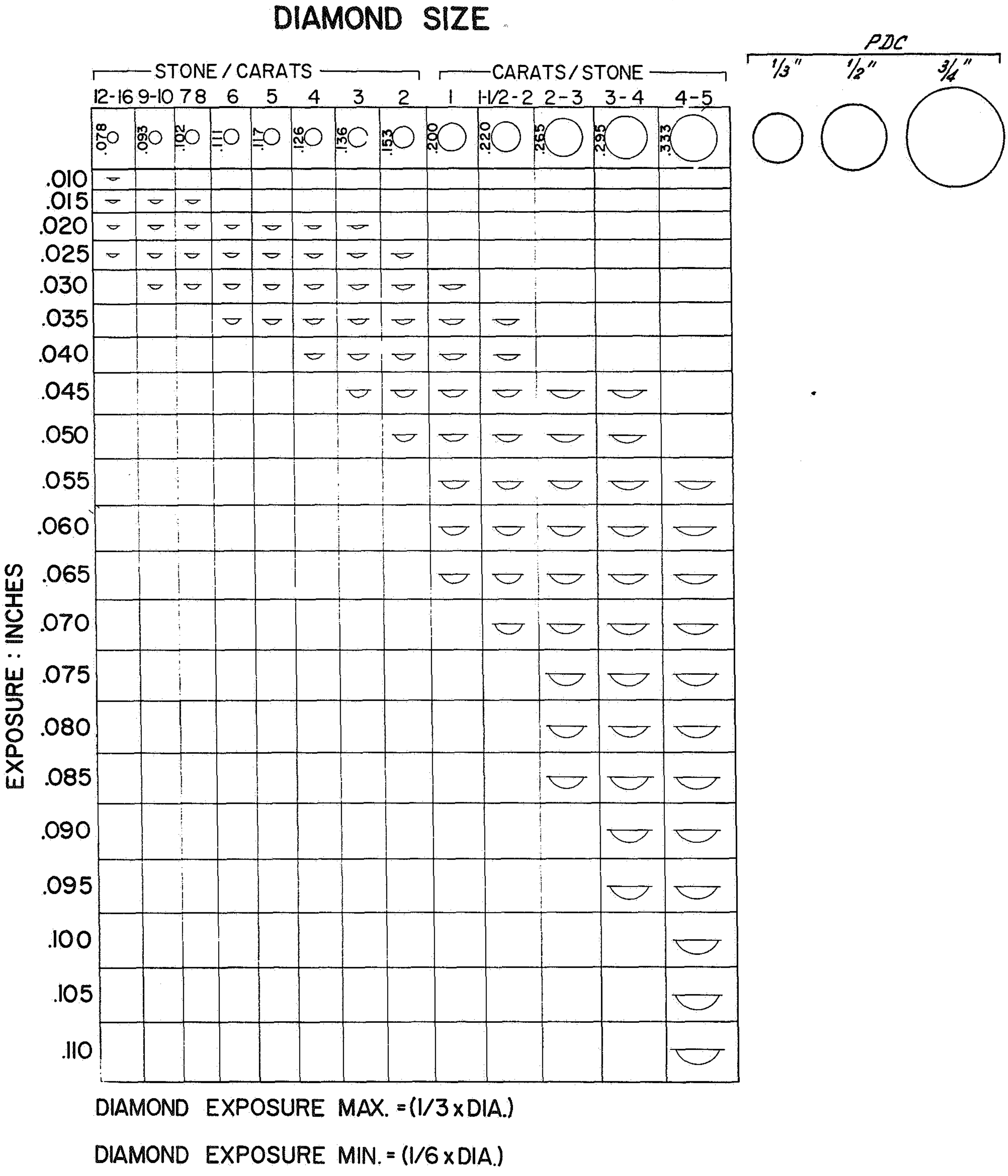

Figure 5: Cross section of exposed diamond.

The starting product consists of very fine and randomly oriented diamond grains. The grade of the particles can be 1-10, 100 microns, in fact any size or any combination of sizes. The size of the grains is the first characteristic of the future "PDC" blank (see below). As diamond growth must be made by a solvent catalytic process to be economical, a liquid metal alloy is needed in the reaction cell. Cobalt is often used as the solvent. The final concentration in metal is the second characteristic of the "PDC". Other ingredients may be added and new composite products are now under investigation.

Two polycrystalline products are now produced: the "PDC" (called in DBS "Diapax") and the "TSD" (called in DBS "Tripax").

The "PDC" is a diamond layer backed up by a substrate of tungsten carbide (WC/Co). It has limited temperature usage.

The "TSD", called thermostable diamond, is an agglomeration of grits without back up but having a different composition or by special treatment for high temperature usage (see chapter Tripax).

To evaluate the quality of the various types of PDC existing on the market, DBS uses a small mining rig with high RPM (rotations per minute) in specific types of formation (actually mainly limestone (Fig. 6, 7, 8). Systematic Quality Control tests on each batch of PDC and TSD diamonds supplied, are explained in Lorent (this volume).

3.2.2.2. Diapax

They consist of a diamond layer 0.5 mm to 1 mm thick fixed to a 2.8 mm or thicker "WC" substrate. The first available blanks were cylindrical in shape with a diameter of 13.3 mm. Other shapes were then made available through flats cutting by electro-erosion (WEDM process) (Pl. 1, photo 4-5).

It took the manufacturers several years from the earlier "compax" to solve the bond failures between the diamond layer and the carbide substrate. Afterwards, it took another few years to develop the right process to attach the "PDC" blanks to the infiltrated matrix. Manufacturers develop special slugs that could be pressed into the matrix but that did not provide much flexibility in bit design, but that technique allows bit repairability, which gives a major advantage over conventional matrix bits when cost per foot against rock bit is composed.

DBS developed a special back-up which takes up smoothly the differential expansion between the diamond layer and the infiltrated WC.

The high-skilled suppliers seem to be at roughly the same level of competence: De Beers - General Electric - Sumitomo. Other suppliers are known on the market: Megadiamond (Megapax), US Synthetic Corp (Terracut) and others including Eastern countries (CIS, China....).

Linear expansion coefficients

Diamond layer: 3,8 10^{-6}/°C.
Diamond: 3 to 4 10^{-6}/°C.
WC substrate: 6,5 10^{-6}/°C.
Back-ups: 8 - 10.10^{-6}/°C
Back-ups vary according to diamond concentration & WC/Co composition.
Infiltrated WC 12.10^{-6}/°C.

As we can see, the manufacture of the "PDC" bit is a complex technique, especially when large size bits or large size "PDC" cutters have to be manufactured. Producers or users of PDC cutters are now changing the simple flat geometry. DBS has developed a special cutter called the "claw cutter". This particular cutter has been designed to reduce the friction of carbide back-up when the "PDC" wears out. This avoids heat development in the back-up and reduces the wear rate of the "PDC" (Pl. 1, photo 6).

Advantages:

- good wear resistance (due to different wear mode than natural diamond, that is by microchipping and consequent self sharpening of the very thin layer of diamond) which is further enhanced bu the diamond back-ups which increase the self sharpening capability of the whole cutting element (Diapax + back-up).

- good shock resistance enhanced by the insert WC/Co back-up to the diamond layer.

- good cutting and chips cleaning features; the latter being rather inherent in geometrical configuration and in shearing mechanism of rock cutting.

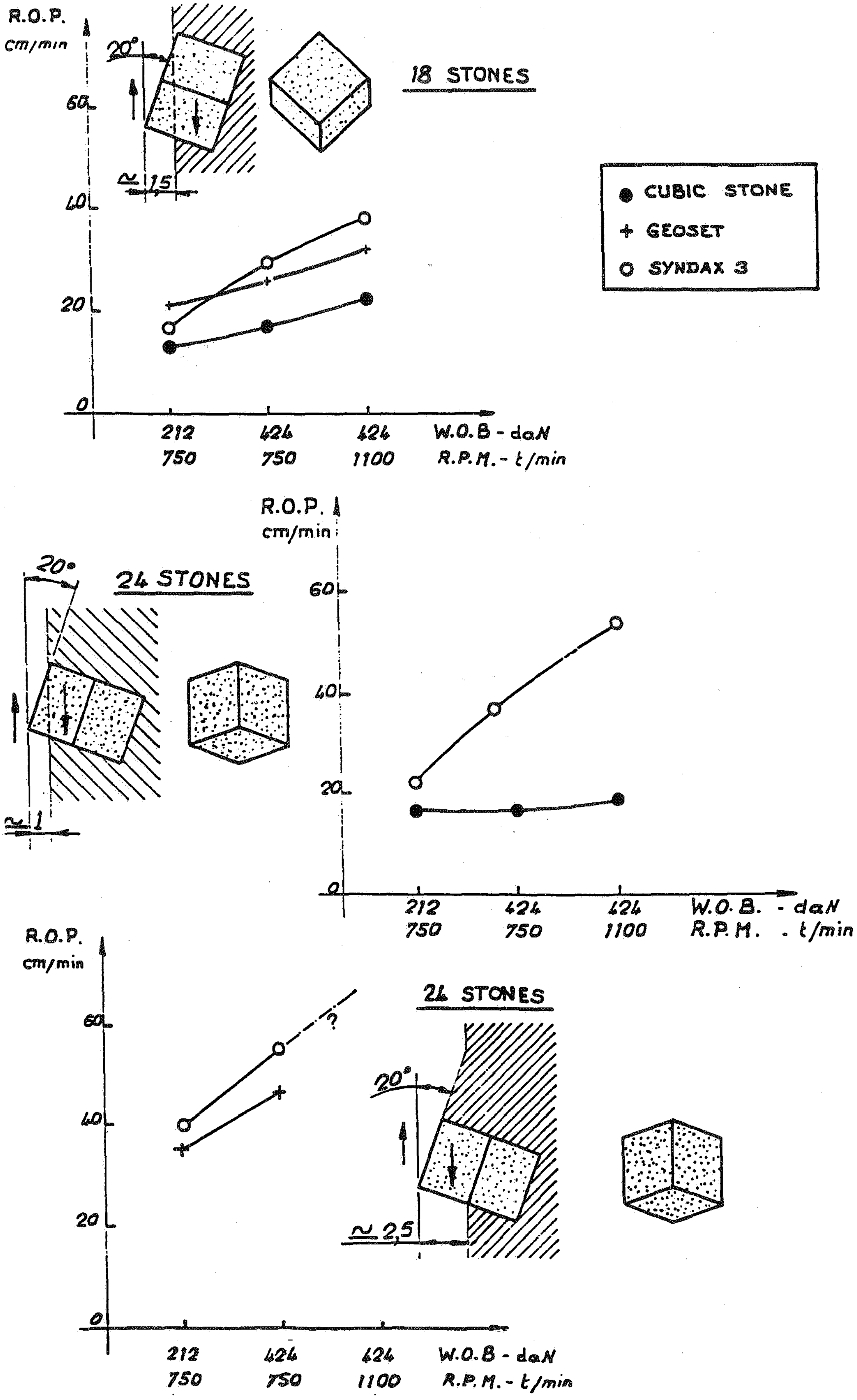

Figure 6: Drilling performances of cube stone, PDC and TSD materials in function of cutting edge.

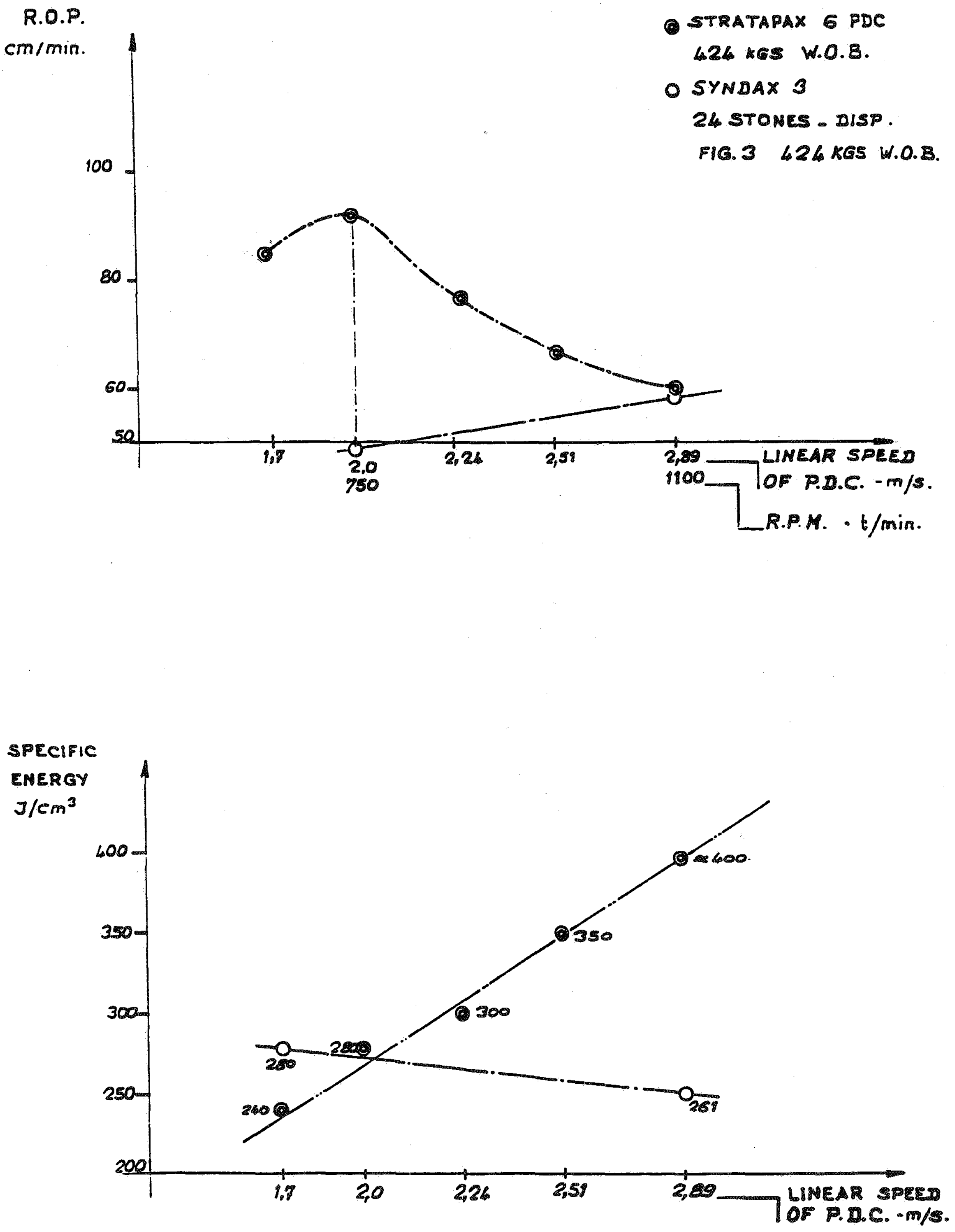

Figure 7: Drilling performance of PDC (Stratapax) and TSD (Syndax).

- good cooling of the cutting edge, the PDC acting as a heat sink (the larger the PDC, the better the cooling possibilities).

There is a clear relationship between grain size and basic properties (Lorent, this volume, fig. 4). Small grains size give a higher abrasion resistance. A typical representative of this group is the Stratapax 28 series of GE. Larger sizes give more shock resistance, like the Stratapax 25 series of GE. Other types are looking for the compromise between those extremes, like for Syndrill from De Beers.

Limitations

These are mainly due to the catalyst (10 % weight Co) left in the "matrix" of the blank.

This Co has an important differential expansion with respect to diamond and is a graphitizing agent for diamond (catalyser). So, the diamond layer temperature should not exceed 750°C, which is likely to occur at the cutting edge with bad cooling conditions, when the Diapax is working by abrading or when rock hardness is too high. In fact, in these conditions, thermal degradation is thought to be the major cause of blanks wear.

As far as the manufacturing process is concerned, "PDC" does not allow any infiltration of the blanks due to the high temperature of infiltration (1100°C). Blanks are then fixed to the back-up with a low temperature braze (700°C). The braze failure could be considered as another limitating working temperature for the blank but, normally, the 750°C temperature limit should be reached first on the working edge of the diamond layer. With ultrasonic control of the brazed joint, the risk of a bad joint has disappeared completely.

Although the initial 13,3 mm round blanks already give rise to several other shapes, new sizes appear which will permit a broader range of bit configurations. Already, a size as large as 2 inches is available.

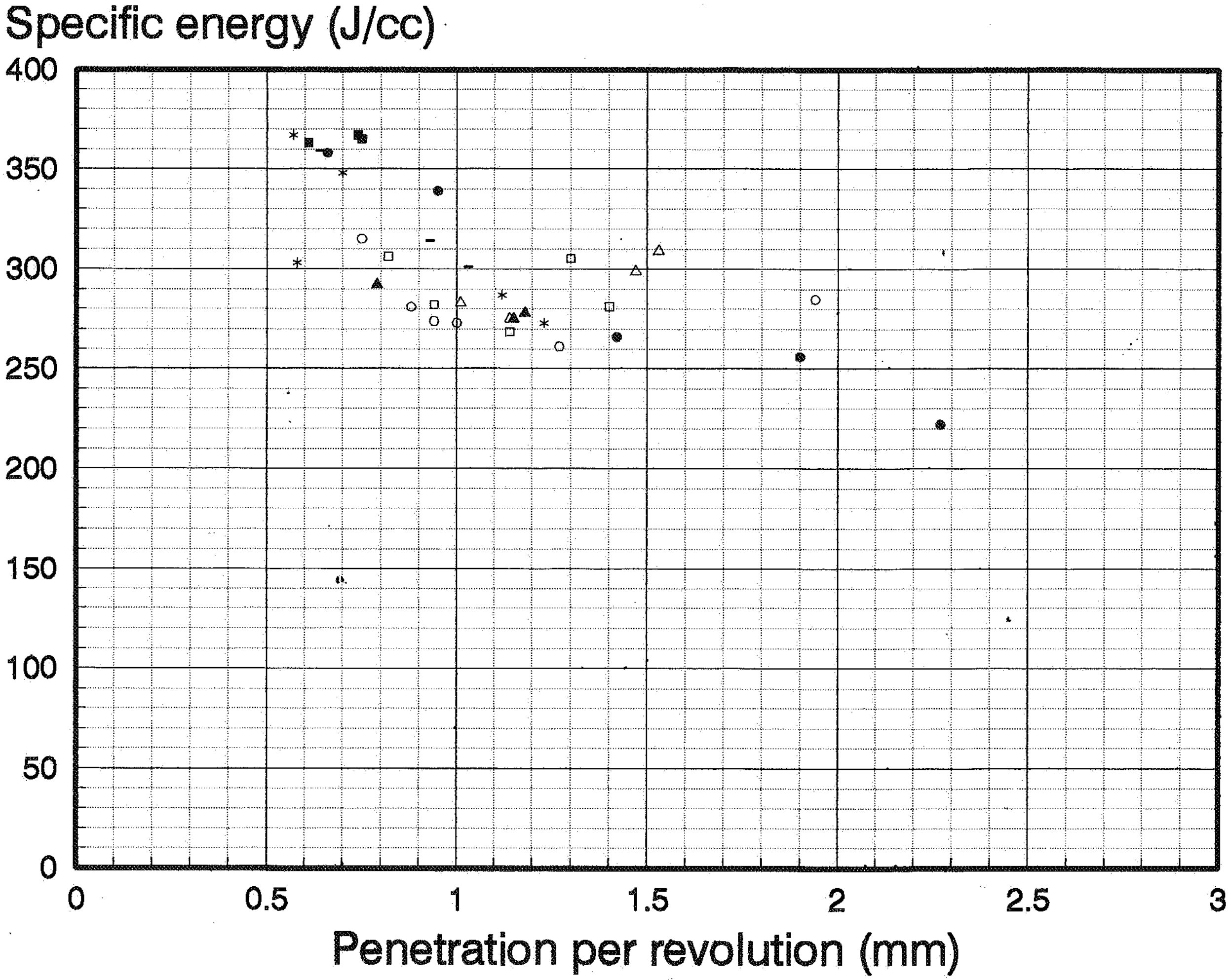

Figure 8: Drilling tests in the "Pierre Bleue", a limestone with compressive strength of 1600 kg/cm^2, showing wide range of results obtained with different types of cutters existing on the market.

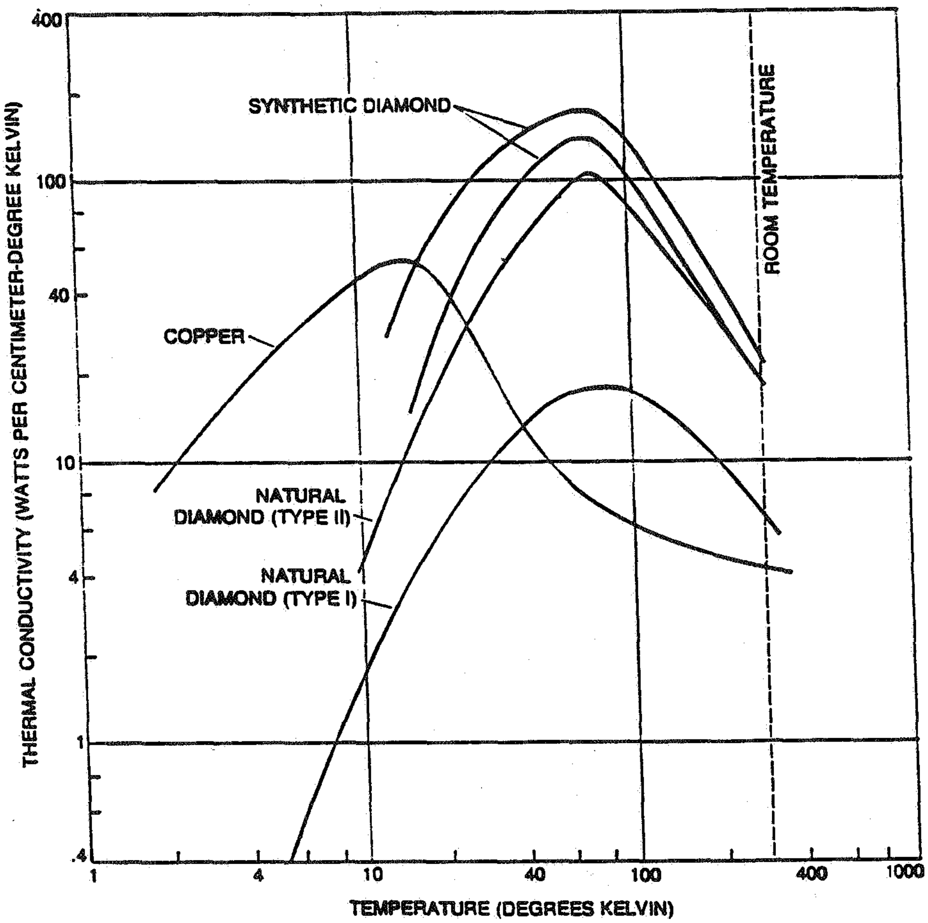

Figure 9: Thermal conductivity of diamond is the highest of all known materials through a wide range of temperatures. Unlike metallic conductors such as copper, diamond conducts by transmitting vibratory motion through the fixed elements of its crystal structure; it is a conductor of photons, the quants of vibratory energy. Type II and synthetic diamonds are better conductors of heat than type I diamonds because type I crystals contain impurities that scatter photons. Diamond also differs from metals in that it is an electrical insulator.

3.2.2.3. Tripax

Owing to the Diapax "heat" limitations and, consequently, in order to reduce manufacturing costs, especially those relevant to the Diapax attachment, manufacturers developed thermally stable polycrystalline diamond material which could be infiltrated straightforward such as surface set natural stones. This is named Tripax in DBS applications (Pl. 1, photo 7).

Since Tripax material was born a few years ago, we are still on the learning curve, trying to determine its exact applications which do not appear to be as wide as earlier expected. This is due mainly to its faster wearing rate than other PDC. But, as we still are in the early stage as compared to the maturity of Diapax and natural diamond, new developments are expected and will certainly broaden their current application range.

The different generations of tripax are hardly comparable.

The ***first generation*** still contains the metal or metal alloy used for the crystal growth process. Tripax of that kind are no more used. (That product can only be found in Diapax).

Geoset [3]

The ***second generation*** is obtained by leaching the material from the frist generation. The Geoset material is produced by General Electric in the same way as PDC but, this time, without carbide substrate. The Geoset polycrystalline product still contains Co, which has a much larger thermal expan-

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[3] Geoset is a registered trademark of General Electric for Cobalt-leached polycrystalline material.

sion coefficient than diamond (3 to 4 times the diamond). This means that, when heated, the cobalt will create cracks within the polycrystalline diamond material. Also, the cobalt at high temperature can act as a graphitizing agent for the diamond. To eliminate all these detrimental problems, General Electric decided to eliminate the cobalt by acidification to the polycrystalline compact at high temperature. So, all the metal traces have been removed. This product can now be used at high temperature but, unfortunately, it is porous and therefore very sensitive to oxygen. This requires special precautions at the manufacture.

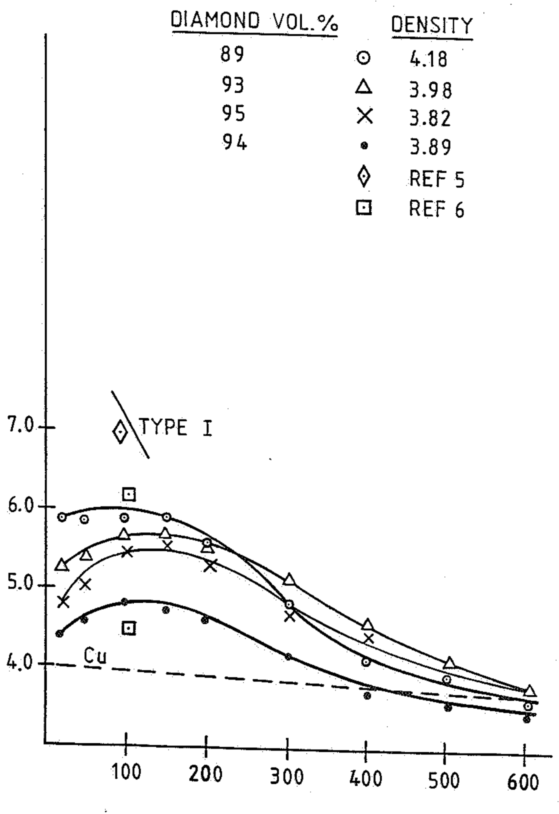

Figure 10: Thermal conductivity of PDC with temperature (horizontal scale: temperature [°C]; vertical scale conductivity [W/cm°K].

Syndax

This product of the ***third generation***, produced by De Beers and some Asian producers, tries to combine the polycrystalline structure with a ceramic material. As mentioned before, the diamond grit agglomerates with Cobalt for the Geoset, which creates thermal expansion problems.

Property	Al_2O_3	Al_2O_3 + TiC	SiALON	Tungsten carbide (K10)	Syndax	Diamond
Density (5g.cm-3)	3.91	4.28	3.20	14.70	3.43	3.52
Compressive Strength (GPa)	4.00	4.50	3.50	4.50	4.74	8.68
Fracture Toughness (MPa.m05)	2.33	3.31	5.0	10.8	6.89	3.4
Knoop Hardness (GPa)	16	17	13	13	50	57/104
Young's Modulus (GPa)	340	370	300	620	925	1141
Modulus of Rigidity (GPa)	153	160	117	258	426	553
Bulk Modulus (GPa)	243	232	227	375	372	442
Poisson Ratio	0.24	0.22	0.28	0.22	0.085	0.07
Thermal Expansion Coeff. (10-6.K-1)	8.5	7.8	3.2	5.4	3.8	1.5 4.8
Thermal Conductivity (W.m 0K-1)	25	35	20-25	100	120	500 2000
Wear Coefficient	0.76	0.92	0.91	0.79	2.99	2.14/5.49
Thermal Shock Resistance	0.60	0.62	3.17	10.2	7.44	24.5

Table 2: Mechanical properties of syndax 3 and other hard materials.

On this problem, De Beers decided to replace Co catalysers with Silicium which has a thermal expansion coefficient close to diamond. This means that it is not a necessity to remove the silicium from the polycrystalline material. So, the product can be used as it is produced from the synthesis. The only problem that could arise is the graphitization process but the content of Si is calculated in such a way that it is transformed into SiC during the synthesis. The small amount of silicium left after synthesis is not large enough to create problems. If this intergrowth product is exposed to oxidation for a long time, diamond is eliminated and a solid structure of Silicon carbide appears. Therefore this product is not porous it has maintained its polycrystalline aspect (high isotropic strength) and can be used at high temperature (1100°C). But, this product is not anymore self sharpening. It acts as a tough natural cube stone, with a much higher shock resistance (Table 2). The two interlocked structures thus give a very interesting toughness and other attractive properties, including the thermal stability of non-porous diamond in presence of oxygen.

Tripax Applications

- Medium hard formation that can still be destroyed by shearing. Due to their shock resistance , cutting speed can be maintained as compared to natural cube (Fig. 6, 7).

- Medium abrasivity.

- Due to light weights required, they are suitable wherever deviation tendencies exist. This is even more true because "Weight on bit" does not need to be increased as fast as on natural stone when wear progesses.

Other advantages are their larger shape and dimensions availability.

Currently, tripax materials are used on a regular basis as reinforcement on wear sensitive areas of the infiltrated matrix or as replacement for cube stones but in conjonction with round stones on mixed setting bits.

The major problem we face with these products in comparison with natural diamond is price. It is strong limitating factor for the moment, especially in large size products.

Material	W/(m* °K)
Diamond	
Diamond monocrystal	600 to 2100
natural diamond	-
Type I	600 to 1000
Type II	1900 to 2100
synthetic diamond	
medium quality	600 to 1000
high quality	1000 to 2000
PDC with cobalt	
GE	500
coarse gr. stratapax 25..	550
fine gr. stratapax 28..	480
De Beers (syndrill)	400
PDC leached type Geoset	160
Composite Syndax 3	120
For comparison	
Copper	400
Tungsten Carbide	100
Steel	46
Alumina	25
Silicium Carbide	5
Graphite	50
Granite	.4
Cement	.1
Glass	.9

Table 3. Thermal conductivity results of the actual product on the market. Most natural diamand boart types are from type 1 whereas high quality natural diamond West African types are from type 2.

3.2.2.4. Polycrystalline diamond limitation

A very important property of diamond is the thermal conductivity (Table 3). The PDC diamond layer has a much lower thermal conductivity than natural diamond. This is why it is much more sensitive to temperature and drilling parameters and mud type. It is recommended to have a good cooling on the PDC face when used on turbine. Great precaution should be taken when turbodrilling in oil base mud due to lower cooling properties of the mud (Fig. 2).

The Tripax material has even a much lower thermal conductivity. This indicates that the Tripax bit should preferably be used in rotary drilling with a good cooling system.

Further development is necessary to improve the properties of all these materials (Figs 9-10).

Cutting action of the diamond

The three major methods of cutting action are the following (Pl. 1, fig. 8).

Abrading:

This method is usually applied for extrat hard rock coring impregnated bit. It uses a lot of energy because the formation is grinded in small fragments. Specific energy in this cutting process is very high (> 1.000 joule/cm^3).

Compressive strength:

This method is applied also for hard formation. The mode of destruction of the formation is by punching. Also the fatigue of the rock by compressive cycle is an important factor. Again in this case, specific energy is high (> 750 joules/cm^3).

Shearing:

This method of destruction is the most economical energetically, using 5 to 12 times less energy than the other ones. It is applied to soft till medium hard formations and, in the hard part of that range, the limitation is the diamond quality. PDC, TSD and cube stone are types of diamond that cut formations by shearing. The large PDC size compared with the size of cube stone allows the producer of diamond bits to compete with rock bits and take a definite advantage on the rock bits, mainly because the cutting action of these new products is more favorable than the rock bit. Unfortunately, many rigs in operation are not yet adapted to modern bit possibilities. A special vertical shearing process has been used in DBS, to produce a large step bit called "LX". We have called it informally the "Schreiner" process as it resembles the Schreiner hardness test.

The specific energy for the cutting process could be very low, close to the compressive strength of the formation. It is generally below 500 joules/cm^3). It is also important to investigate the stress distribution in the rock during the shearing process as these studies allow to improve the geometry and the interaction between the cutters.

4. CONCLUSION

WHAT SHOULD BE KEPT IN MIND BY THE OPERATIONAL PEOPLE IN THE DRILLING INDUSTRY

"Diapax" and Tripax" bits can sustain very high horse-power per square inch. Tests have been realized till 12 HP per square inch. We have not yet found the maximum horse-power that a PDC or a TSD product can sustain. We have to realize that bit performance is in direct relation with downhole horse-power within specific parameter ranges (RPM - WOB etc.).

"TSD" or '"PDC" products do not accept heavy shocks but are in general better than natural diamond bits on this point of view. This is why it is critical to handle the bit on the rig properly. Wrong manipulations can cause bit cutter to be destroyed on the nose and the gage and this could be highly detrimental for the bit life. Great care is taken when packing these products in the manufacture.

Thermal conductivity of both products is less than natural for diamond but they are capable of handling more horse-power per cutter than natural diamond. This is why parameters should be controlled properly (lower RPM-avoid turbine motors for TSD in general-when high horse-power is required in hard formations avoid using PDC in oil base mud with turbine when high horse-power is required on the bit). Avoid in general turbine motors for large size bits: 12 1/4 is a maximum limit. 17 1/2 PDC or TSD bits should never be run on a turbine motor.

Load per cutter can be very high:

For PDC - 400 kgs.
For TSD - As high as 100-120 kgs per cutter (3 spc).

New developments of PDC and TSD shape and product composition will continue. It is a prime objective for DBS to continue to assist the synthetic diamond producer in defining the tendency and the mechanical properties of the new product. Also, it became necessary to produce synthetic diamond on a research scale with the goal to develop proprietory products.

Furthermore the chemical vapor deposition (CVD) technology already produces high quality grit and diamond fibers for applications in the electronic industry. It is recognized that diamond layers can be deposited on steel or other substrates. We can envisage an additional improvement of diamond bits by applying the CVD technology.

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Numerous internal reports of De Beers, Diamant Boart and General Electric have been utilised for the compilation of this publication.

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PLATE 1

Photo 1 : Rough boart ; the nice stones shown are extracted from the "Congo" mines. Rough boart stones are agglomerates of very impure crystals.

Photo 2 : Chemically polished boart with rounded shape for high wear resistance.

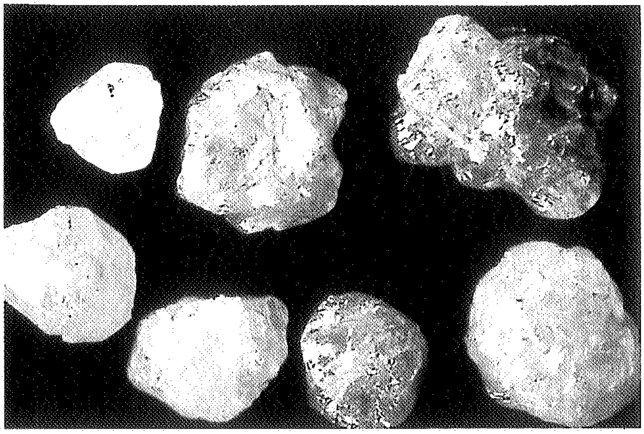
Photo 3 : "Drilling" (J designation in Diamond Boart) showing a very pronounced degree of crystallisation up to dodecahedral and octahedral shapes.

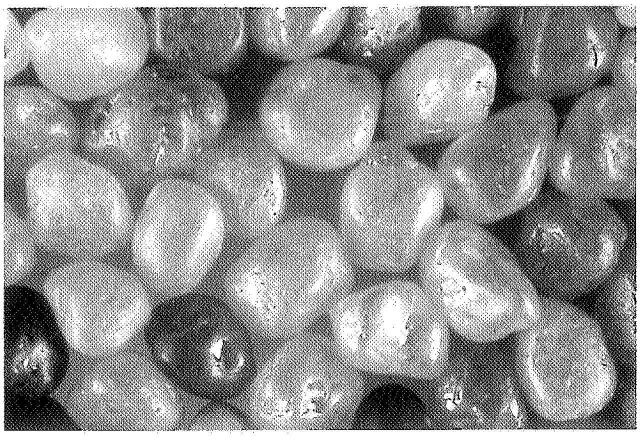
Photo 4-5 : PDC polycrystalline diamonds ("Diapax") consisting of a thin diamond layer fixed to a tungsten-carbide substrate. The first available blanks were cylindrical in shape with a diamanter of 13.3 mm.

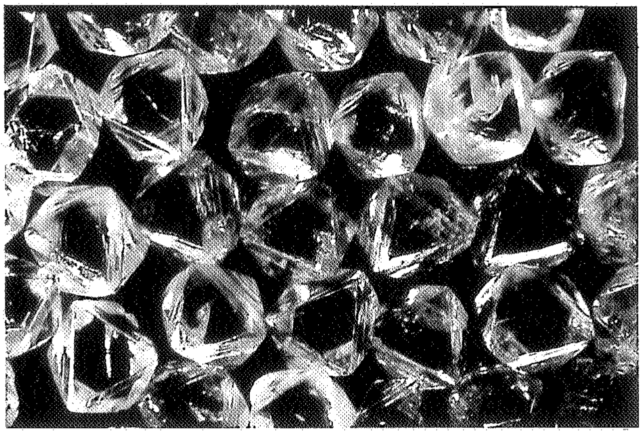
Photo 6 : "Diapax claw cutter", designed to reduce the friction of the carbide back-up when the "PDC" wears out.

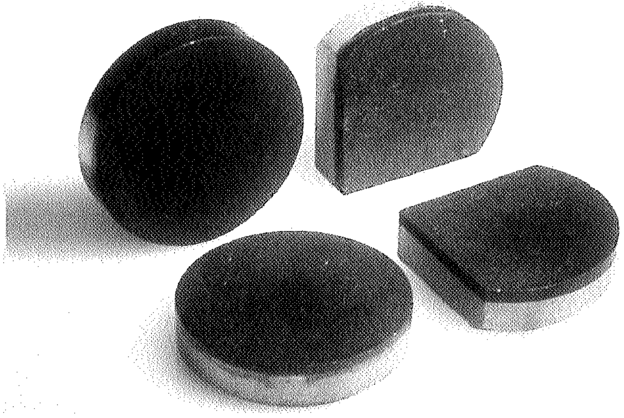
Photo 7 : "Tripax", thermally stable polycrystalline diamonds.

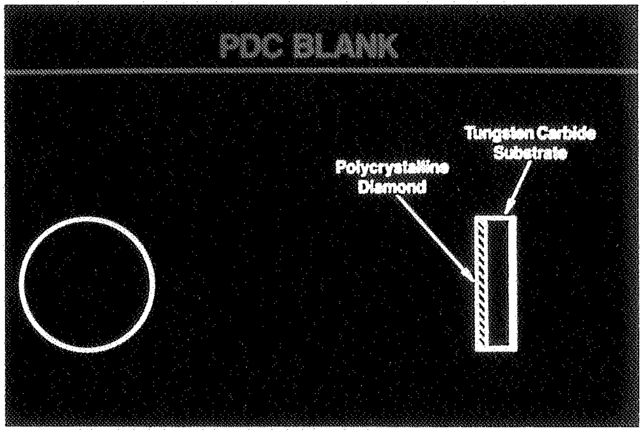
Photo 8 : Cutting action of PDC diamonds.







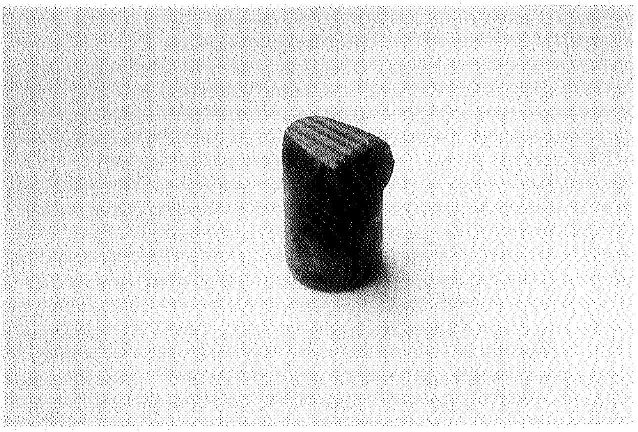


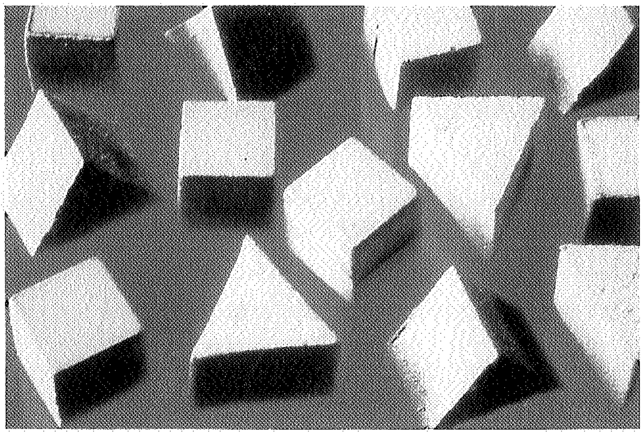


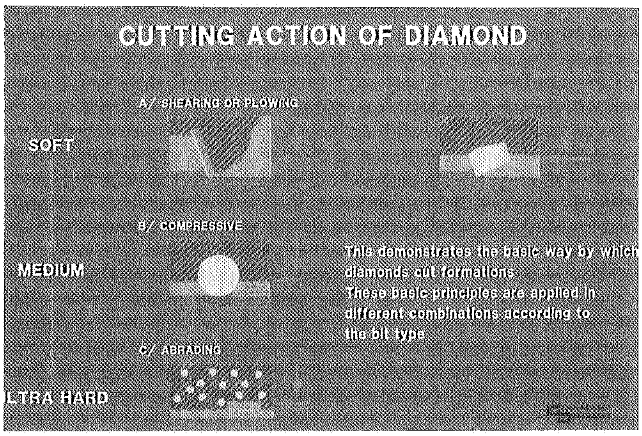
PDC BLANK

Tungsten Carbide Substrate

Polycrystalline Diamond







CUTTING ACTION OF DIAMOND

SOFT

A/ SHEARING OR PLOWING

MEDIUM

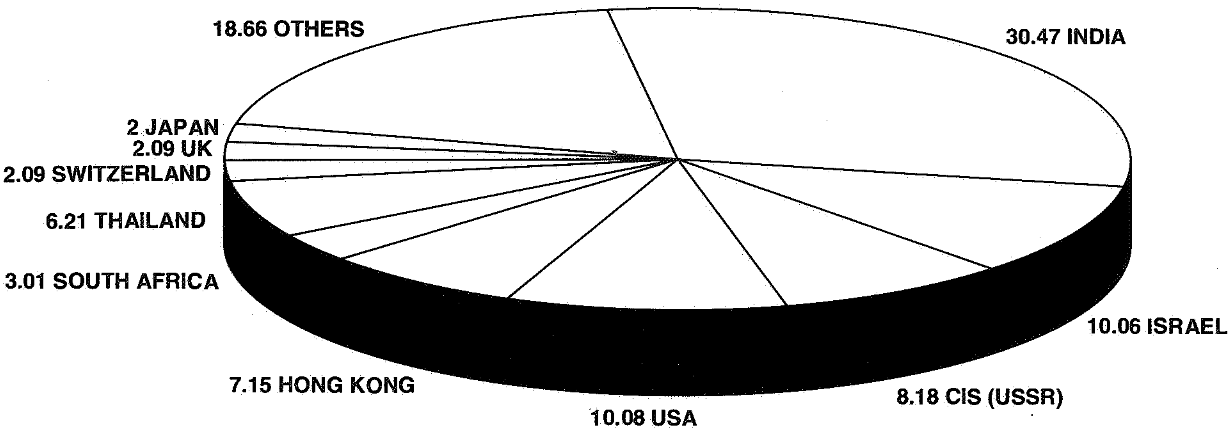
B/ COMPRESSIVE

LTRA HARD

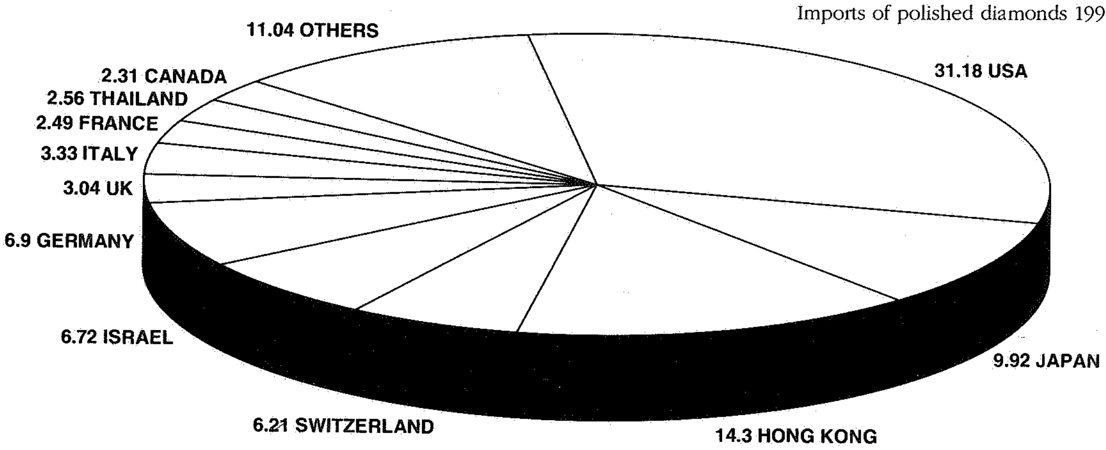
C/ ABRADING

This demonstrates the basic way by which diamonds cut formations
These basic principles are applied in different combinations according to the bit type

Trade Figures
Total turnover: 492,194,015,001 BEF or 15,302,970,000 USD
Total imports: 241,937,409,210 BEF or 7,520,100,000 USD
Total exports: 250,253,515,128 BEF or 7,782,870,000 USD
Imports polished diamonds: 91,846,519,685 BEF or 2,854,850,000 USD
Exports polished diamonds: 114,175,772,784 BEF or 3,550,860,000 USD



Imports of polished diamonds 1992



Exports of polished diamonds 1992

ANTWERP WORLD DIAMOND CENTER IN FIGURES 1992

Employment
Total employment for trade and industry: 30,000
Employees in the industry: 3,750
Apprenticeships (estimate): 53
Number of students in the Antwerp diamond schools: 107
Diamond companies: 1,500
Workshops (manufacturers): 380
Dealers and brokers: 3,500

Importance worldwide
Contribution to total Belgian exports: 7%
Part of world supply rough diamonds: 85%
Part of world supply polished diamonds: 50%
Part of supply natural industrial diamonds: 40%

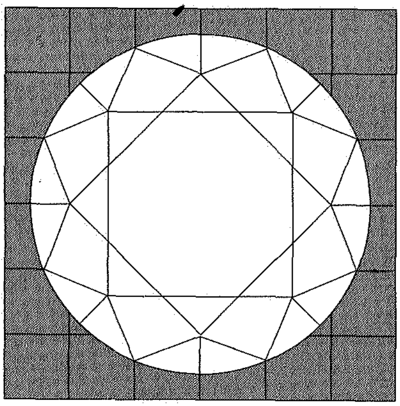
Infrastructure
Diamond bourses: 4
Professional organizations: 7
Trade unions: 2
Specialized diamond banks: 6
Diamond schools: 3

Antwerp Diamond Index (31.12.92)
1 ct: 247.4
1/2 ct: 263.0
1/4 ct: 109.7
Melees: 134.0
Small brilliants: 142.2

ANTWERP WORLD DIAMOND CENTER

Antwerp, world diamond center

In the heart of Europe, famous as port and trade center, Antwerp is the world's capital for diamond and the major wholesale center for precious stones worldwide. Antwerp's diamond industry currently handles approximately 85 % of rough supplies by volume and around 50 % of CSO sale by value and an estimated 40 % of world trade in natural industrials, realising an annual turnover of more than 15 billion $. The diamond sector guarantees 7 % of total Belgian exports and is one of the most important ambassadors and economic mainstays of the country.[1]



Diamond trade

Near the Central Station is located the Antwerp diamond center: a Square Mile, with a unique infrastructure, housing 1500 diamond firms and 4 diamond bourses. The wide offer and the mutual competition result in sharp prices and optimal service.

Diamond industry

Despite a considerable reduction in work force, thousands of highly skilled Antwerp diamondworkers are active to keep up the international quality label "Cut in Antwerp". Based on a tradition of 5 centuries, a constructive vision on the future, efficient education and applied high technology research guarantee this high quality label.

Diamond High Council (HRD)

The Diamond High Council is the umbrella organisation, the spokesman and impetus of the Belgian diamond sector. The various departments have well defined tasks:

Diamond Office (import/export)
Public Relations
Certificates
Gemmological Institute
Social Secretariat & Industry
Scientific and Technical Research Center (WTOCD) and Comdiam established in Lier.

Hoge Raad voor Diamant vzw,
Hoveniersstraat 22 - B-2018 Antwerpen.

The provincial diamond museum

The Antwerp diamond museum clearly visualises the fascinating world of diamonds, from the mine to your finger. Open 7 days from 10 a.m. to 5 p.m. Free entrance. Lange Herentalsestraat 31 - Antwerpen.

Diamant Museum Grobbendonk (Kempen)

Open Mon-Fri 9 h - 16 h
Sat. 10 h - 13 h 30
Sun. 10 h - 16 h
Entrance fee 30,- BEF.
Oude Steenweg 13A - 2280 Grobbendonk.

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[1] data kindly provided by the Diamond High Council. References: Carl Pearson - Antwerp, a status report, and Annual Report, 1992, in Antwerp Facets, March 1993.

THE DIAMANT BOART GROUP

Diamant Boart S.A., founded in 1937, is a 100 % subsidiary of Sibeka (Société d'Entreprises et d'Investissements S.A.) which in turn is a member of the Société Générale de Belgique Group, the principal shareholder of which is the Compagnie de Suez.

The name of the Company refers to the boart, a type of industrial diamond found in abundance in the ground of Zaïre and which the Company had the task of exploiting. This diamond, which did not meet the standards for jewellery, offered exceptional physical properties for industry.

The diamond

A diamond is a sign of wealth....

As, moreover, it is rare, it is hardly surprising that, since the age of the alchemists, men have attempted to counterfeit it. It was, however, only in 1953 that they succeeded, for the first time, in creating the necessary pressure and temperature conditions for its formation. Since then, production of synthetic diamonds has developed to the point of nowadays being able to cover 90 % of industrial requirements.

As for the annual consumption of Diamant Boart's superabrasives - natural diamond, synthetic diamond and CBN (cubic boron nitride) taken altogether - nowadays it is close to 20 million carats (4 tonnes).

The Company's Structure

The Company is currently structured into business units, responsible on an international level for R & D, production, marketing and sales.

The B.U. Stone manufactures and sells a complete range of tools and equipment necessary for working on natural stone (marble, granite, sandstone, etc.), from quarrying, through slabbing, sawing, drilling, milling and surfacing, up to final polishing.

The Construction B.U. produces the equipment and diamond tools (saw blades, drill bits, cables) for sawing and drilling reinforce concrete, stone materials in general and many other building and civil engineering materials such as, for example, concrete-coated steel pipelines.

The B.U. Industries delivers its production to multiple industrial sectors, including the automotive industry, aeronautics, electronics, optics, metal machining, glass and ceramics..

The Strategic Material Department not only supplies the B.U.'s and other clients outside the Group with superabrasives and metal powders, but guarantees the quality of these supplies and places its central EVA (Expertise, Verification, Analysis) characterizing laboratory at the disposal of both.

In April 1991 Diamant Boart and Sandvik disposed of DB Stratabit, a manufacturer of equipment for the oil industry in which they were joint shareholders and, likewise, in November 1992 Diamant Boart disposed of its mineral exploration equipment activities (Craelius).

Some noteworthy contributions to industry

One of Diamant Boart's first and most important contributions to the marble industry was the introduction, in 1955 of the diamond frame saw blade, a tool which nowadays equips thousands of frame saws throughout the world. This achievement was repeated some fifteen years later with the introduction of the first frame saw blade using synthetic diamonds.

The development of the first diamond cables was another important contribution by Diamant Boart to the stone quarrying industry. There followed in succession the cable with an electrolytic deposit (1968), the diamond-impregnated cables for marble (1980) and for granite (1985).

The diamond shoes for surfacing/polishing continuous lines (currently under development) will likewise constitute a major contribution by the Company to the stone industry.

Still to be mentioned are the low noise saw blades for granite, the belts for quarrying machines, the saw blades welded by laser microfusion. The latter have equiped all kinds of portable saws used on building sites since 1984 and offer the advantage of dry working.

The particularly high standards of precision of the Diamant Boart rotary wheel dressers (especially those of inverse galvanic type) are nowadays making the reputation of Diamant Boart wherever precision and mass production are the prime objectives.

Diamant Boart throughout the world

A continuing policy of research utilizing very latest technologies has allowed the Group to achieve the leading position on a world scale, 95 % of Belgian production is exported.

In addition to its production centre at Forest (Brussels, Belgium), integrated with the Company Headquarters, the Group has five manufacturing centres in Europe (France, Greece, the Netherlands, Spain, United Kingdom) and two in the United States (Missouri and South Carolina).

Diamant Boart markets products and provides services in all these countries as well as in Germany, Italy, Portugal, Canada, Singapore, Hong-Kong and Japan. A minority shareholder in subsidiaries set up in Mexico, Argentina, India and in the Philippines, Diamant Boart is further represented by agents in numerous other countries.

The consolidated turnover is in the region of 10 milliard BEF, 30 % of which is obtained from the Stone industry, 50 % from Construction, 15 % from the Industries sector and 5 % from the sale of superabrasives and sundry products. One-third of sales by B.U. Construction involves machines (manufactured in France and the United States), and two-thirds diamond tools.

Of the consolidate turnover, 65 % is earned in Europe, 30 % in North America and 5 % in the Far East.

Personnel employed is over 2,000 people, 37 % of whom are in Belgium.