

SINTERED DIAMOND TOOLS – THE PAST, PRESENT AND FUTURE

The methods of making diamond tools have undergone a remarkable development since the invention of synthetic diamond in the mid-1950s. The current review summarises key historical, recent and ongoing trends and developments in sintered diamond tools. The report concentrates on tools used within the stone and construction industries which, being the main consumers of metal-bonded diamond tools fabricated by powder metallurgy (P/M) technology, have always fuelled advances in tool design and production technologies.

Keywords: Sintered diamond tools, synthetic diamond, tool design

1. Introduction

Until the early 1990s the diamond tool industry had been mainly threatened by the very high cost of diamond, whereas the price of other raw materials, e.g. cobalt and cobalt-based matrix powders, used in most professional and non-professional applications, had remained at an acceptable level. The sharp rise in the price of cobalt initiated an intensive search for cheaper matrix materials. Concurrently, rapid improvements in the cubic type multi-anvil high pressure equipment and its large-scale implementation for diamond synthesis, resulted in tremendous price cuts on the diamond supply side. As most of the diamond grits have always been used for sawing natural stone and concrete, new production techniques that emerged in the stone and construction industries in the 1990s brought pressure on toolmakers to develop new manufacturing routes and refine the existing tool designs in order to do the job faster, more accurately and at less cost. To meet these objectives, efforts were directed toward substituting cobalt matrix with iron-base and copper-base alloys, overcoming poor diamond retention and achieving its better distribution in the matrix, and developing new tools for hard-rock slabbing to render the slab production faster and cheaper with the minimum waste of expensive stones.

The replacement of cobalt-based matrix with other metals could lead to a loss in diamond tool performance, however, the steeply rising contribution of cobalt to the tool fabrication costs triggered an intensive search for cheaper matrix powders. This

resulted in development of finely dispersed, pre-alloyed copper-base and iron-base powders. Since 1997, when the first powders were launched commercially under brand names *Cobalite* and *Next*, the number of specific grades has almost quadrupled to cater for the wide diversity of tool manufacturing techniques and application conditions. The inherently high manufacturing costs of chemically pre-alloyed powders affect their final price, which remains a major concern for their use. This attracts attention to markedly cheaper pre-mixed powders which, as their pre-alloyed counterparts, are steadily formulated and refined to couple the excellent consolidation behaviour with field performance similar to cobalt.

For a tool that is wearing ideally, the fraction of lost diamond grits should not be too large, i.e. less than 30%. The anchoring of grits by mechanical means often proves insufficient to retain high-grade blocky crystals used to cut granite and tough ceramics. To date two methods have been used to solve this problem. The most common practice involves coating the crystals with a thin film of a strong carbide former, such as titanium, chromium or silicon, which increases metallurgical bonding and diamond protection from surface graphitisation and prevents attack by matrix components aggressive to carbon. The coatings differ in thickness, method of deposition and are being applied to grits throughout the expanding range of qualities to suit a wide spectrum of applications and tool fabrication conditions. Parallel developments are being seen in thermal treatment of the crystals during consolidation of the

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diamond impregnated component. By roughening their surface it is possible to improve the hold on diamond grits by increasing friction at the diamond-matrix interface. Until quite recently this method was rarely practiced due to a high risk of harming the crystal integrity and strength. However, the latest application of this technique to the fabrication of wire saw beads has proved effective [1].

Other benefits can accrue to tool performance from uniform distribution of diamond crystals in the metallic matrix. This can be achieved by using either grits encapsulated in the matrix powder or diamond placing technology. The encapsulation route eliminates diamond clustering and their premature loss, and offers the freedom to vary the composition of discrete layers within the encapsulated pellet in order to improve grit retention and protrusion.

A real breakthrough in manufacturing saw blade segments, wherein diamonds are equally-spaced and arrayed in a regular pattern, was made in 2004. At that time the elimination of random grit distribution alone resulted in marginal improvement in tool performance and did not justify increased production costs. Later enhancements in cutting rate and tool life became possible due to optimising the number of diamond impregnated layers and arrangement of crystals within these layers. Nowadays specially designed segments are making significant inroads into the problem of slabbing granite with diamond frame saws. The new diamond blades cut faster than the traditional steel shot frame saws with lower kerf loss.

Since the 1980s diamond wire sawing technology has been gaining ground in the stone industry, primarily for quarrying of stone blocks and their further division, as well as in various construction applications. Further machine and wire developments were needed for hard-rock sawing. Stationary mono-wire machines were first developed and used for block squaring and profiling. Multi-diamond-wire (MDW) machines are the newest type of equipment used for granite-block slabbing, where they mainly compete with traditional steel shot frame saws. In recent years much effort has been made to reduce the wire thickness. Through improvements in the construction of MDW machines, bead formulation and design, rope splicing and plasticisation, it is now possible to produce wires thinner than 4.5 mm.

Today, in the third decade of the 21st century, we see that engineers are continually developing raw materials, tools and tool production routes to improve their application behaviour and introduce them into new application areas. Examples include iron-rich powders free-sintered to near-full density below 950°C, self-brazing powders dedicated to free-sintering of diamond beads, new small-diameter bead designs, as well as saw blade segments and core drill segments fabricated by high-pressure high-temperature sintering technology.

2. Historical background

The successful application of ultrahigh pressure to synthesise diamond grits and their commercialisation in 1957 [2] was

a real milestone in fabrication and application of sintered diamond tools. Since that time, metal-bonded diamond-impregnated composites made by various P/M routes have been increasingly used in machining stone and ceramics, for cutting concrete, road repair as well as for exploration of gas and oil. In 1990 the overall consumption of industrial diamond reached the volume of around 380 million carats, but still remained limited by the high price of the synthetic material utilised for more than 90% of industrial applications [3].

The situation changed during the 1990s, when consumption of synthetic crystals tripled, reaching 1 billion carats in 2000 [3]. A large share of the market was taken by a rapidly growing Chinese production. In the early 1990s tool fabrication costs were mostly affected by the high prices of diamond grits and, to a lesser extent, hot pressing consumables, whereas the contribution of cobalt or cobalt-base matrix powders, ideally suited for the vast majority of applications, remained at an acceptable level. The then forthcoming drop in the price of synthetic grits and a sharp decrease in consumption of graphite moulds and electrodes, due to the application of vacuum/nitrogen gas chambers in the hot pressing equipment, focused more attention on the steeply rising contribution of cobalt to the tool fabrication costs. The instability of the cobalt market initiated an eager search for cheaper options. Consequently four iron-base and copper-base cobalt substitutes were developed and marketed under the brand names *Next* (Eurotungstene 1997 [4]) and *Cobalite* (Umicore 1998 [5]). Concurrently, significant improvements in grit quality and its retention in the metallic matrix were achieved through the evolving sophistication of diamond synthesis and crystal coating technology.

In the new millennium the market for diamond tools has grown even faster. Although the data released for the years 2004-07 is inconsistent [6-8] there is no doubt that in the late 2000s production of industrial diamond reached the impressive volume of nearly 10 billion carats, with China emerging as the world's leading producer, with the annual production approaching 9 billion carats [8]. This became possible due to the massive use of large-volume, cubic-anvil high-pressure apparatus [9] in which a system of previously used external frames of tie bars was replaced by Chinese engineers with large castings connected by cylindrical pins. These castings were mass produced without extensive machining needed for the original tie bar/base design, giving cost advantages directly benefiting high volumes of production [10]. As a consequence of availability of synthetic grits in very large volumes and varieties, prices dropped by ~80% [11], which transformed diamond into a commoditised product. It is noteworthy that the tremendous drop in the price of synthetic grits manufactured in China, to around 5 US¢ per carat in 2010, was accompanied by significant improvements in quality, catching up with the products offered by the world's leading producers [9].

Premature tool wear due to a non-uniform distribution of diamond crystals in the metallic matrix has always been a major concern. Early attempts to solve this problem by using metal powder-coated diamonds were made in the 1980s and 1990s

[12-14]. This work was continued in the 2000s. The emphasis was placed on fabrication of dual-layered pellets containing a WC-rich coating on the diamond crystal. The usage of a wear resistant inner layer resulted in longer tool life, due to improved grit retention and protrusion [15].

A more ambitious approach to controlling grit distribution in the metallic matrix was proposed by two Korean toolmakers, i.e. EHWA Diamond Industrial Co. Ltd. (ZENESIS Project) and Shinhan Diamond (ARIX Project). New ideas of placing diamond grits in three dimensional patterns were developed in the late 1990s and patented in the early 2000s [16-18]. Over the next few years proprietary technologies were mastered to position the grits within the segment in an optimal manner. Significant improvements in both cutting rate and tool life were achieved after proper sequencing of diamond-containing and diamond-free layers and finding the optimum angle at which the rows of diamonds were inclined with respect to the tool working face. The first ZENESIS and ARIX circular blades were launched commercially in 2004 and 2005, respectively. Soon after the ZENESIS technology was extended to other types of tools, including frame saw segments for sawing granite [19]. Over the next few years diamond setting technology was gaining ground due to the commercial availability of fully automated systems [20]. A typical diamond placing equipment includes a volumetric cold press which fills a steel die with a thin layer of matrix powder, sets diamond crystals onto this layer in a predetermined pattern using a perforated suction feeder, levels the powder, puts another layer of powder and diamond on top of the previous one, and so forth. The sequence continues until the preset number of layers is achieved. Then full compaction pressure is applied prior to ejection.

In addition to the significant technological progress in diamond synthesis, tool design and its fabrication techniques, the first decade of the new millennium witnessed a major breakthrough in the recognition of the diamond wire saw as a powerful tool in sawing granite and other difficult-to-cut stones. At the turn of the 1970s and 1980s, when diamond wire was successfully used for quarrying and squaring of marble blocks in Carrara [21], there was a common opinion that igneous rocks would never be cut economically with diamond wire, due to the high cutting forces. At that time, granite blocks were cut into slightly oversize slabs with traditional steel shot frame saws, while diamond-segmented frame saws were used exclusively on softer stones, such as marble, dolomite or sandstone. The then forthcoming machine and wire developments enabled widespread commercialisation of mobile single-wire machines for granite extraction in the quarry and stationary mono-wire machines used for block squaring and/or profiling [22]. A prototype MDW machine fitted with 10 \varnothing 10 mm wires was tested in 1994, but extensive use of such equipment in slabbing of granite blocks as a replacement for steel shot frame saws came in the 2000s [23]. As the technology evolved, MWD machines taking 58 \varnothing 6.7 mm wires were soon marketed by Bideseimpianti S.r.l. in Italy [21], which was a significant breakthrough in machine design.

3. Current trends and market perspectives for sintered diamond tools

In 2009, the slowdown in global economies mainly affected the European stone and construction industries. Until 2013, 28 EU countries suffered a 16% drop in the production of natural stone and 9% in the construction industry [24]. Concurrently, China took over the leading position in the international stone industry from Italy, increasing its global market share to 42.4% in 2015 [24]. However, after a period of unrestrained growth, stone production in China began to show a reverse trend [25]. The overall demand for diamond tools also declined, following the downturn in stone and construction industries. The output of Chinese synthetic diamond fell from 16.8 billion carats in 2014 to 13.9 billion carats in 2016 [26] and bounced back to 18 billion carats in 2018, accounting for 98% of the global supply [27].

With further improvements in the Chinese synthesis technology, toolmakers should rather expect better value for money than significant price cuts on the diamond supply side. Therefore, development of inexpensive matrix powders and cost-effective fabrication routes are prime concerns for economic production of sintered diamond tools.

Historically, cobalt has been the most valued matrix metal, but recent figures reveal for the Italian market a decreasing use of cobalt, which accounts for 25% of 350 tons of powders consumed annually by the diamond tool industry [25]. Pre-alloyed powders constitute the largest share of 40% [25], but, despite obvious advantages over pre-mixed powders (35% share), they are expensive to produce. Therefore intensive research is currently in progress to substitute for the commercially practiced hydrometallurgical methods, which generate large quantities of environmentally harmful wastes (salts). Emphasis is also placed on lower content, or complete elimination, of expensive alloying elements such as cobalt or nickel.

The method developed at AGH [28] eliminates the expensive hydrometallurgical stage at which homogeneous mixtures of hydroxides, or oxalates, are formed. It has been replaced by an inexpensive mechanochemical synthesis of hydrogen reducible compounds which provides more freedom in the selection of powder chemical composition. The process relies on high-energy milling of substrates prior to annealing in a reducing gas. Examples of fully pre-alloyed powders developed and manufactured [29] by means of this method are illustrated in Fig. 1.

The powders can be pressureless sintered to a closed-pore state at 900°C and yield materials which meet acceptance criteria for the fabrication of high quality tool components, e.g. diamond saw beads. After cold compaction at 200 MPa and pressureless sintering at 900°C in hydrogen, the Fe-Cu-P powder reaches a density of 7.74 g/cm³ and a hardness of 212 HV. Interestingly, on quenching from the sintering temperature, the alloy can be age hardened to 312 HV. The tin-modified Fe-Cu-Sn-P version has been developed for efficient and economical fabrication of diamond saw beads. A green diamond-impregnated tube made from the self-brazing powder can be firmly joined to a plain carbon steel sleeve during sintering, thereby eliminating the

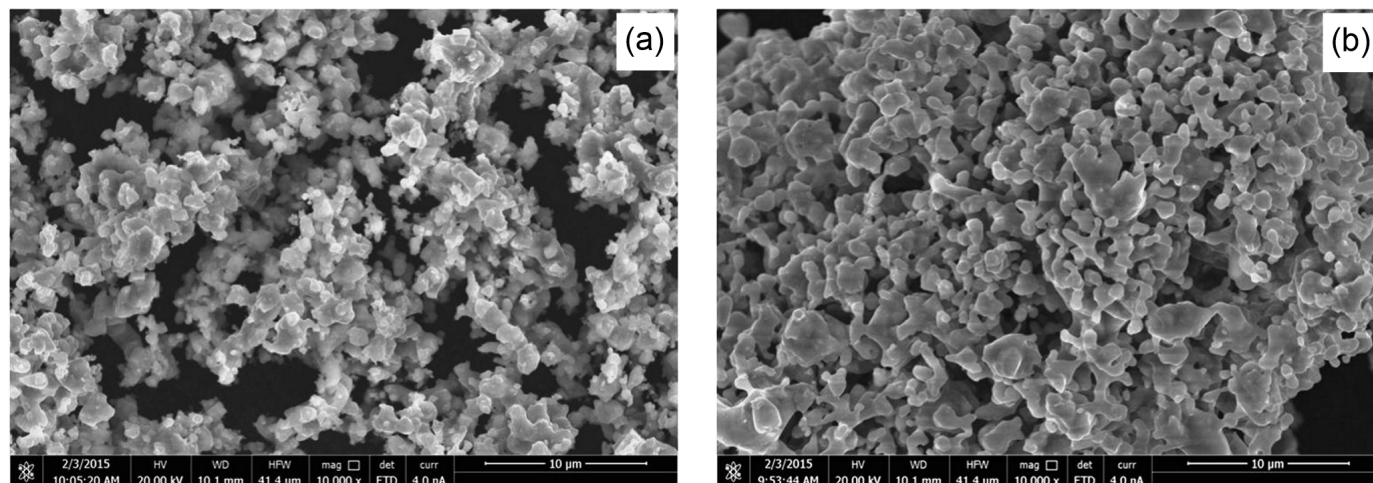


Fig. 1. Fe-Cu-P powder containing 95.5% iron (a) and “self-brazing” Fe-Cu-Sn-P powder containing 90% iron (b)

need for a subsequent brazing operation. In the as-sintered condition the self-brazing alloy reaches a density of 7.94 g/cm^3 and a hardness of 230 HV.

Ball milling can also be used in the manufacture of inexpensive matrix powders for fabrication of diamond segments by the hot press route. It has been shown that ball-milled iron-base Fe-Ni-Cu-Sn-C and Fe-Mn-Cu-Sn-C powders can be hot pressed to near-full density at 900°C , to yield materials characterised by high resistance to abrasion [30]. Until recently it has been common practice to use fine Co-WC powders, typically containing 20-40% WC, for the fabrication of diamond segments for cutting/drilling abrasive materials such as sandstone, fresh concrete, asphalt, porous ceramics, etc. The combination of a very low price, ease of densification and high abrasion resistance makes the ball-milled iron-base powders ideal candidates to replace expensive Co-WC mixtures.

The consolidated pre-alloyed powder matrices have finer microstructures and higher mechanical strengths compared to those made from pre-mixed powders. The latter option has usually the merit of being cheaper. Moreover, pre-mixed powders show flexibility in alloy composition, enabling creation of unique microstructures and properties, have better pressing characteristics, can readily be customised to fit specific wear conditions, etc. Therefore there is enough incentive for toolmakers to continue developing proprietary powder compositions. Combinations of the base carbonyl iron powder with pre-alloyed bronzes, elemental copper, tin, nickel and WC are most often used for a wide variety of applications.

There has been a lot of machinery designed for working stone, ceramics and construction materials over the past decade. The industry sees novel CNC workcentres, bridge saws, wire saws, etc. The machines themselves can be remotely diagnosed by the manufacturers via the internet or monitored to provide information about working conditions and service demands. The new processing techniques dictate novel tool designs which have to meet unique application requirements.

Unlike any other types of tools, a wire saw for hard-rock sawing has undergone many modifications in recent years to

improve its performance. Today wire sawing technology is undergoing widespread commercialisation. In addition to granite block extraction at the quarry face, block squaring and profiling on mono-wire machines, it is increasingly used for finish slabbing of blocks on MDW machines. Unlike single diamond wires, which replace large circular diamond blades, the MDW technology is still being developed and has yet to reach its full potential. As there is still a considerable number of steel shot frame saws in operation, diamond multi-wires must also compete with the patterned diamond frame saws, which can be used on the traditional pendulum motion frames after their modification [31].

In frame sawing the reciprocating movement of the blade facilitates diamond pullout since there is no build-up of matrix tail, and forces act on diamond grits in alternate directions. The patterned diamond segments, so-called ZGS (Zenesis Gang Saw) segments, contain diamonds arranged in groups of at least two crystals. Short distance between the working grits, of 2-3 times the grit size, changes their loading conditions and enables formation of a supporting matrix tail, similar to that on circular saw blades. The effect of cutting conditions on diamond loading is explained schematically in Fig. 2.

The ZGS system has advantages over traditional steel shot frame sawing in that the yield of usable stone is bigger by 15%, the cutting rate is 3-5 times higher, and there is far less varia-

TABLE 1

Yields of slabs and down-feed rates typical for various granite slabbing methods

Sawing technique	Number of slabs per 2 m block width		Down-feed rate, cm per hour
	Slab thickness: 21 mm	Slab thickness: 31 mm	
Zenesis Gang Saw	76	56	10-15
Steel shot frame saw	66	50	2-5
Multi-wire $\phi 7.3 \text{ mm}$	68	51	20-50
Multi-wire $\phi 6.3 \text{ mm}$	72	53	20-50
Multi-wire $\phi 5.3 \text{ mm}$	74	55	20-50
Multi-wire $\phi 4.3 \text{ mm}$	80	57	20-50

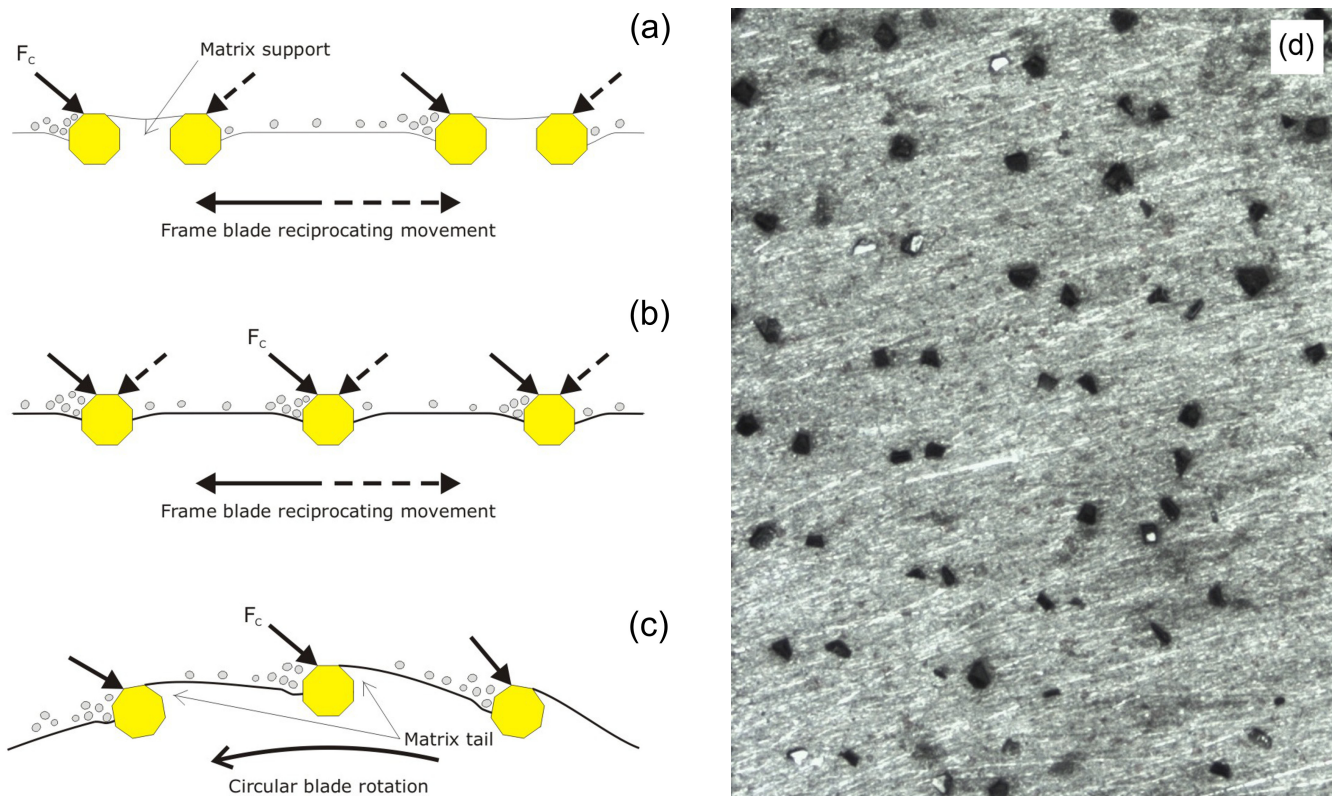


Fig. 2. Diamond loading force (F_c) in frame sawing (a), (b) and in circular sawing (c). (a) ZGS segments: build-up of matrix supports between paired diamonds; trailing grits are not loaded. (b) Conventional segments: undercuts on either side of grits due to alternating loading. (c) Circular blade segments: build-up of matrix tails due to blade rotation in a constant direction. (d) Side view of a ZGS segment

tion in slab thickness and a better surface finish. As presented in Table 1, until recently the ZGS system also outperformed MDW sawing in terms of yield obtained from the stone. In 2017, however, a significant breakthrough in MDW sawing took place with the advent of $\varnothing 4.3$ mm diamond wires installed on a dedicated MDW machine designed and constructed in Poland by Q-TEQ Ltd. (Fig. 3).

In addition to faster cutting, another advantage of MDW systems over frame sawing is quick positioning of wires on the machine, which allows simultaneous production of slabs of different thickness (2-3-4-5 cm and multiples). The benefits of MDW sawing have recently been recognised by manufactur-

ers of stone tiles used for flooring and wall cladding. Although multi-bladed tile sawing machines are still in common use, an unique *Polyone* multi-wire winding system has been designed to perform two simultaneous cuts, in opposite directions, for each wire, in order to produce slightly oversize slabs for further calibration and polishing to a finished tile thickness of 1 cm [32].

Seemingly, diamond multi-wire sawing is now the fastest growing application area for sintered diamond tools [33]. Producers of MDW machines increasingly demand smaller diameter diamond wires to minimise kerf width and maximise the number of slabs that can be sawn from a single block. Apart from this increase in yield, there are also significant economic

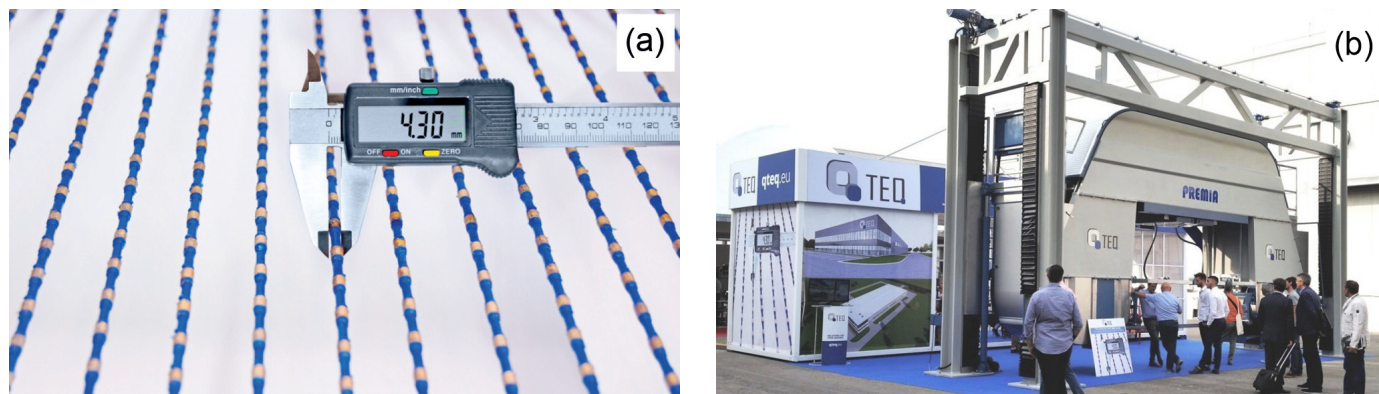


Fig. 3. The thinnest commercial diamond wire (a) and presentation of Premia MDW machine (b) at Marmomac 2017 held in Verona, Italy (Courtesy of Q-TEQ Ltd.)

and environmental benefits to accrue from increased cutting rates and smaller amounts of waste generated.

An undesirable consequence of decreasing the wire thickness is a disproportional reduction in the steel rope diameter. In block sawing, the downward pressure of the wire on the block is kept constant. Assuming the same bead length, spacing and specification, the wire tension force has to be set proportional to its diameter. It means that for the dimensions provided in Fig. 4, the $\varnothing 2$ mm steel rope used in $\varnothing 4.3$ mm diamond wires has to withstand tensile/fatigue loads at least 75% higher compared to those used in $\varnothing 6.3$ mm and $\varnothing 7.3$ mm wires. This gives rise to the urgent need for stronger steel ropes and high-grade diamond beads. The latter include improved bead sintering parameters and optimum selection of matrix powders and diamond grits, with an emphasis on free-cutting characteristics of the tool.

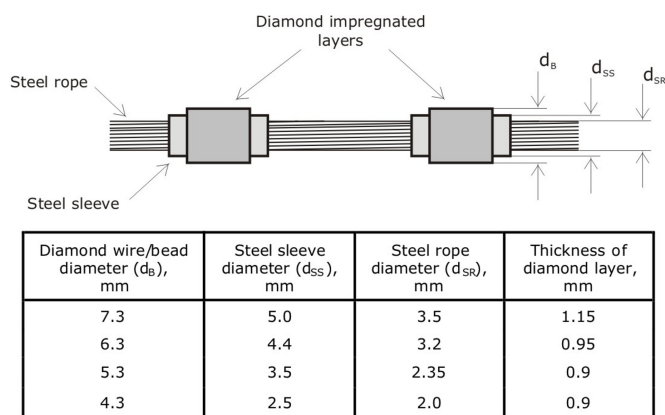


Fig. 4. Typical diamond bead and steel rope dimensions

The commonly used $\varnothing 7.3$ and $\varnothing 6.3$ mm wires may soon be superseded by thinner $\varnothing 5.3$ and $\varnothing 4.3$ mm wires. Therefore major improvements in construction of MDW machines, bead formulation, design and spacing, steel rope strength, rope splicing and wire plasticisation are needed to satisfy the demanding application conditions and increasing customer expectations.

Finding solutions to all these problems is a great challenge for the toolmakers today. Therefore, due to its simplicity, the frame sawing technology still attracts attention of machine and tool designers to meet the challenging needs of granite slab production. The recently proposed modification of the frame movement kinematics (Fig. 5) eliminates the reciprocating cutting action, and thus reduces diamond pullout similarly to circular sawing.

As opposed to the ZGS system, patterned diamond segments are no longer necessary. This simplifies the tool fabrication and lowers its cost.

The preliminary tests on the production of granite slabs started at Granit-Color Ltd. in August 2019 on four reconstructed Gaspari Menotti traditional swing-type frame saws (Fig. 6). The achieved cutting rates and tool lives were comparable or better than that achieved in the ZGS system showing great potential for cost savings. Efforts are underway to reduce the steel blade and diamond segment thickness from 3.5/5.0 mm to 2.5/4.0 mm.

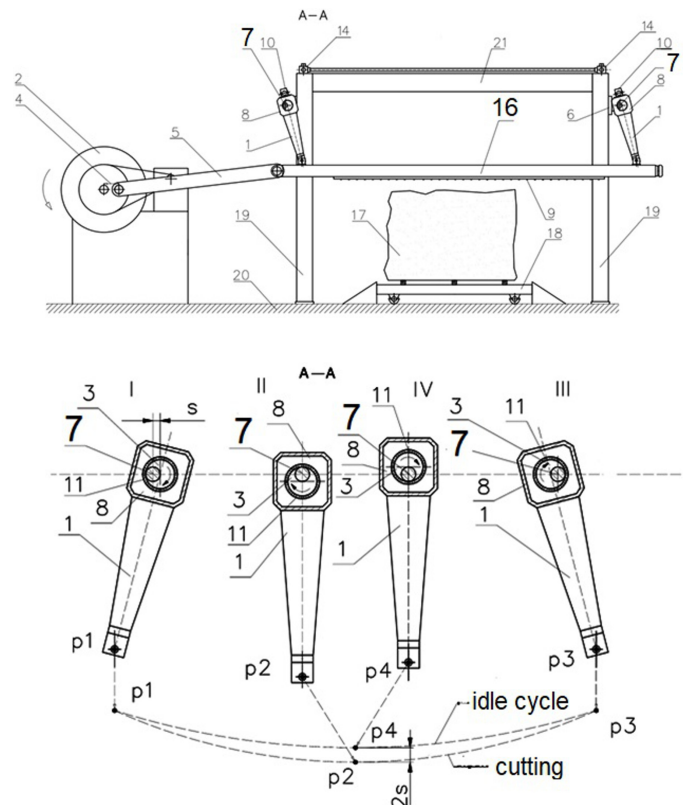


Fig. 5. Pendular movement of a diamond bladed frame (16) modified by eccentric pins (7) which allow the frame to be raised and lowered cyclically [34]

It seems likely that during the next decade the dream of many people working in the stone industry that cutting granite blocks with diamond blades using a simple gang sawing technique shall become reality if the Granit-Color system is brought to a large-scale industrial use.

4. The outlook for the future

The advancements seen over the last decades in diamond synthesis technology have brought down diamond price by two orders of magnitude and led to its large-scale industrial use. As a natural consequence, the matrix powders and tool fabrication technologies have been receiving increasing toolmakers' attention. Therefore, there is considerable interest and activity in development of new and improvement of existing metallic powders and tool fabrication routes today. The matrix powders should combine low price with desired sintering characteristics and excellent application performance, whereas manufacturing technologies are expected to be more cost-effective. On a laboratory basis, diamond-impregnated segments for sawing and drilling have already been manufactured by high-pressure high-temperature sintering technology in China [36-37]. Significant progress recently achieved by Chinese design engineers in the development of the cubic high-pressure apparatus and its adaptation to high-pressure sintering is a good prognostic for future commercialisation of this technology.



Fig. 6. Gaspari Menotti swing-type steel shot frame saws fitted with a novel diamond bladed frame rising system. Granit-Color Ltd. facilities in Ostrowiec Swietokrzyski [35] (Courtesy of Granit-Color Ltd.)

The outbreak of Covid-19 pandemic in China, and its spread outside China in the early weeks of 2020, triggered a global economic recession freezing production and trade activities for a few months. The diamond tool sector is highly integrated with China, the world's largest synthetic diamond and diamond tool production centre, therefore bringing the Chinese production and supply networks back on track remains a priority. Despite the present signs of stagnation in stone and construction industries, they will presumably continue to grow and consume the majority of sintered tools with an increasing demand for diamond wires.

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