Diamond cutting tools wear behaviour analysed through diamond particles characterisation

Pisk, Matija

UNIVERSITY OF ZAGREB – FACULTY OF MECHANICAL
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Matija Pisk

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Mentori: Student:

Prof. dr. sc. Božidar Matijević, dipl. ing. Matija Pisk
Dr. sc. Ivan Kumić, dipl. ing.

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Izjavljujem da sam ovaj rad izradio samostalno koristeći znanja stečena tijekom studija i navedenu literaturu.

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Love you all!

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DIPLOMSKI ZADATAK

Student: **MATIJA PISK** Mat. br.: 0036475455

Naslov rada na hrvatskom jeziku: **Analiza trošenja dijamantnih reznih alata pomoću karakterizacije dijamantnih čestica**

Naslov rada na engleskom jeziku: **Diamond cutting tools wear behaviour analysed through diamond particles characterisation**

Opis zadatka:

Diamond cutting tools are, amongst other, used in a variety of tooling applications in construction such as sawing, coring and drilling of masonry materials, limestone and concrete. Due to the different mechanical and tribological properties of these materials, it is crucial to choose the right tool for each application. Performance of the cutting tool is tightly interlinked with characteristics of diamond particles themselves.
In the theoretical part of this thesis, it is necessary to summarize the important characteristics as well as the limitations of diamond cutting tools in order to provide an extensive insight into the current status of diamond tools' field of research. Furthermore, the characterization of diamond particles at various stages of tool wear is to be investigated experimentally, and identified characteristics correlated with the exploitational behaviour of the tool. Utilising optical microscopy in conjunction with advanced imaging analysis techniques, insight into the wear mechanism of diamonds needs to be provided. The results obtained from this research could better explain the behaviour of diamond tools in actual applications and thus provide invaluable data for further research and development of this type of product.
Please indicate any help received when writing the thesis.

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prof. dr. sc. Božidar Matijević	dr. sc. Ivan Kumić	prof. dr. sc. Biserka Runje

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Symbol	Unit	Description
K	Kelvin	Temperature
Pa	Pascal	Pressure
Kg	Kilogram	Mass
m	Meter	Distance
ρ	Kg/m^3	Density
K_{IC}	$MPa*m^{1/2}$	Fracture toughness
N	Newton	Force
“	Inch	Distance
TI	Figure of merit	Toughness index
W	Watt	Power
rpm	1/s	Revolution per minute
v	m/s	Peripheral speed

SUMMARY – CROATIAN VERSION

U ovom diplomskom radu istaknut je pristup istraživanja i razvoja dijamantnih materijala za upotrebu u reznim alatima. "Dijamantni rezni alati" mogu se koristiti u različitim građevinskim primjenama kao što su piljenje, jezgreno brušenje ili bušenje na zidanim materijalima poput opeke, vapnenca (homogeni materijal) i betona (heterogeni materijal).

Dijamantni alat sastoji se od čelične osnove (kao što je jezgra pile, cijev za jezgru ili kotača) i reznog elementa (neke vrste dijamanta). Ti su rezni elementi u većini slučajeva kompoziti sa metalnom matricom odnosno segmenti s ugrađenim česticama dijamanata kao nosača iznimne tvrdoće, a time i visokih abrazivnih svojstava. Dvije glavne karakteristike dijamantnih alata su brzina rezanja i vijek trajanja. Te su karakteristike obično recipročne, a dokazano je da je istodobno povećavanje brzine rezanja i vijeka trajanja alata poprilično izazovno.

Provođenjem karakterizacije dijamanata koristeći najsuvremenije tehnike, dobivene karakteristike ocjenjivat će se dovoditi u kontekst ponašanja alata u eksploataciji. Optička mikroskopija, u kombinaciji s naprednim tehnikama snimanja, pruža uvid u bolje razumijevanje stanja trošenja dijamanta aktivne površine umetka tijekom njegovog životnog ciklusa. Ovi rezultati, pod utjecajem različitih arhitektura segmenata i u odnosu na radne parametre poput zakretnog momenta, brzine rezanja i posmaka, osiguravaju potpuno razumijevanje evolucije stanja dijamanata i njihovih procesa degradacije. Ovi će rezultati omogućiti bolje razumijevanje ponašanja i performansi dijamantnih alata u stvarnoj primjeni.

Ključne riječi: dijamant, dijamantni rezni alati.

SUMMARY – ENGLISH VERSION

This thesis highlights an approach in research and development of diamond materials for use in insert tools. 'Diamond insert tools' may be used on different construction jobs for the specific purposes of sawing, coring or grinding on concretes (heterogeneous) and masonry materials like brick and limestone (homogeneous). A diamond insert tool comprises a steel base (such as a saw blade centre, core bit barrel or cup wheel) and cutting elements. These cutting elements are in most cases metal-matrix composite segments with embedded diamond particles, as carriers of extreme hardness and therefore needed abrasive properties. The two principal performance characteristics of an insert tools are cutting speed and lifetime. These characteristics are commonly inverse hence, obtaining a simultaneous increase in cutting speeds and lifetime is proven to be quite challenging.

By performing diamond characterisation using the state-of-the-art techniques, the obtained characteristics will be assessed and used to detect the correlation with the insert tools behaviour. Optical microscopy, in conjunction with advanced imaging techniques, will provide insight into the better understanding of diamond wear state of the insert's active surface throughout its life cycle. These results, influenced by varying geometries of the inserts and in relation with operational parameters like torque, cutting speeds, and feed rates, ensure that the evolution of diamonds' state and its active failure modes are fully understood. These findings will enable better comprehension of diamond tools behaviour and performance in real-life application.

Key words: diamond materials, diamonds insert tools.

1. INTRODUCTION TO CARBON AND DIAMOND

Carbon is a chemical element with the symbol C and atomic number 6 (6 protons and 6 neutrons in nucleus). It is non-metallic and tetravalent — having four electrons available to form covalent chemical bonds. It belongs to group 14 of the periodic table. Three isotopes of carbon occur naturally, ^{12}C and ^{13}C being stable, while ^{14}C is a radionuclide, decaying with a half-life of about 5,730 years, which in some cases, enables precise carbon dating. Carbon is the 15th most abundant element in the Earth's crust and the fourth most abundant element in the universe after hydrogen, helium, and oxygen. Carbon's abundance, its unique diversity of organic compounds, and its unusual ability to form polymers at the temperatures commonly encountered on Earth enables this element to serve as a common element of all known life. It is the second most abundant element in the human body (about 18.5 wt. %) after oxygen [1].

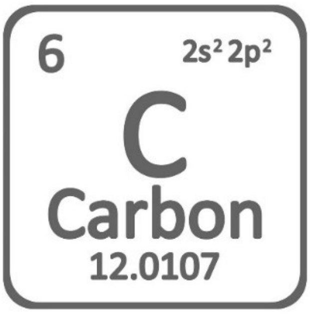


Figure 1: Carbon – elemental information

Atoms of carbon can bond together in different ways, termed allotropes of carbon. The best known are graphite, diamond, fullerene and amorphous carbon.

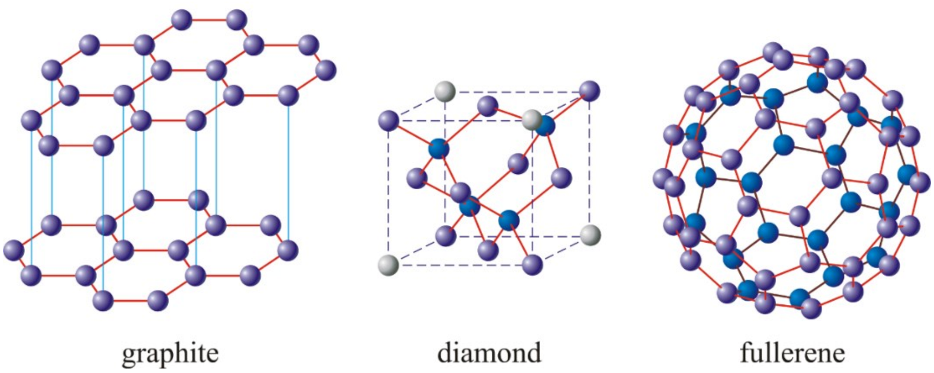


Figure 2: Allotropes of carbon [2]

To fully understand the importance of diamond as a tool material, some notes from history lessons should be taken. In 6000 B.C., diamond was first mentioned in India, in 4000 B.C. diamond use was shown in China, as a sharpening tool for grinding and polishing of burial axes and other metal tools. In Greece, 2500 B.C., the name for diamond appears, “adamas” which means illustrious, unconquerable and unobtainable. It wasn’t until late 1700s, when French scientist by the name of Lavoisier, had an idea to burn a diamond, discovering only carbon as a by-product. Therefore, for the first time in history, mankind knew what the diamond was made of. A few decades later in 1797, British scientist Smithson Tennent connected the graphite with diamond, and stumbled upon interesting effect of allotropy, which enables different structural forms from the same chemical composition [3].

At that time, all diamond was mined from natural deposits, with the best quality diamonds being used for gems in jewellery and the remaining lower-grade diamonds being used for industrial purposes. The inconsistency of industrial diamond, in terms of both availability and quality, was one of the motivations for the research into diamond synthesis. Then, in 1953, a breakthrough occurred. Swedish scientists Liander and Lundblad were successful in synthesising first man made diamond and in 1954, General Electric from USA reported of their own successful synthesis from the same period [4].

In recent times, it is possible to engineer and produce large quantities of diamonds in needed sizes, shapes and strengths.

Figure 3: General electric builds a diamond making press in 1954. [5]

2. DIAMOND PROPERTIES

2.1. Introduction

Diamond is a solid form of the element carbon, allotrope, with its atoms arranged in a face-centred crystalline structure. At room temperature and pressure, another chemically stable solid form of carbon is called graphite.

Diamond has the highest hardness (on Mohs scale 10 out of 10) and highest thermal conductivity of any natural occurring material. These properties are utilized in major industrial applications, in form of tools for cutting and polishing applications.

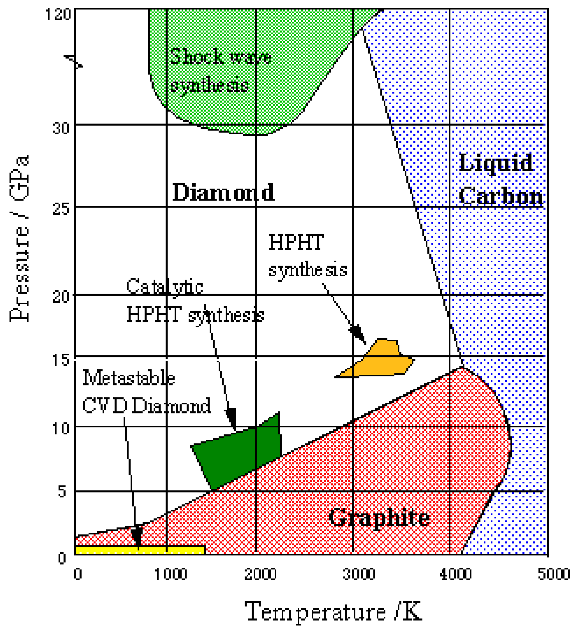


Figure 4: Carbon diagram – Pressure/Temperature [6]

Because the arrangement of atoms in diamond is extremely rigid, few types of impurities can contaminate it (two exceptions being boron and nitrogen, which are used in doping procedure). Small numbers of defects or impurities (about one per million of lattice atoms) are reason for different diamond colours found in nature, such as: blue (boron), yellow (nitrogen-single substitutional atom), brown (high levels of lattice distortion), green (radiation exposure), purple, pink, orange or red. Diamond also has relatively high optical dispersion (ability to disperse light of different colours).

2.2. General properties

Diamond is a solid form of pure carbon (with occurrence of small amount of impurities) with its atoms arranged in a crystal. Solid carbon comes in different forms known as allotropes, which depend on the type of chemical and/or physical bond. The two most common allotropes of pure carbon are diamond and graphite. In graphite the bonds are sp^2 spin orbital hybrids and are formed in planes with each bound to three nearest neighbours at 120 degrees apart. In diamond they are of sp^3 spin and the atoms form tetrahedra with each bound to four nearest neighbours [7]. Tetrahedra are rigid, the bonds are strong, and of all known substances diamond has the greatest number of atoms per unit volume, which is why it is both the hardest and the least compressible. It also has a high density, ranging from 3150 to 3530 kg/m^3 in naturally occurring diamonds and 3520 kg/m^3 in synthetic pure diamond. In graphite, the bonds between nearest neighbours are even stronger but the bonds between planes (Van der Waals force) are weak, so the planes can easily slip past each other [8]. Thus, graphite is much softer than diamond.

Diamonds have been adapted for many uses because of the material's exceptional physical characteristics. It has the highest thermal conductivity and the highest sound velocity. It has low adhesion and friction, and its coefficient of thermal expansion is extremely low. Its optical transparency extends from the far infrared to the deep ultraviolet and it has high optical dispersion. It also has high electrical resistance. It is chemically inert, not reacting with most corrosive substances, and has excellent biological compatibility.

2.3. Thermodynamics

The equilibrium pressure and temperature conditions for a transition between graphite and diamond are well established theoretically and experimentally. The pressure changes linearly between 1.7 GPa at 0 K and 12 GPa at 5000 K (the diamond/graphite/liquid triple point), shown in figure 4. However, the phases have a wide region about this line where they can coexist. At normal temperature and pressure, 20 °C (293 K) and 1 standard atmosphere (0.10 MPa), the stable phase of carbon is graphite, but diamond is metastable and its rate of conversion to graphite is negligible. Without the use of a catalyst, at temperatures above 4500 K diamond rapidly converts to graphite. Rapid conversion of graphite to diamond requires pressures well above the equilibrium line: at 2000 K, a pressure of 35 GPa is needed [9].

2.4. Mechanical properties

Diamond is a material with quite unique sets of mechanical properties, the most important ones being hardness, toughness, thermal and chemical stability which are readily exploited in production of cutting and coring tools.

2.4.1. Hardness

The extreme hardness of diamond in certain orientations makes it useful in materials science, as diamond indenter embedded in Vickers and Rockwell hardness tester, which opposed to Brinell's hardness tester, enables measurements of all material types.

Diamond hardness depends on its purity, crystalline perfection and orientation: hardness is higher for flawless, pure crystals oriented to the (111) direction (along the longest diagonal of the cubic diamond lattice) [10]. Therefore, whereas it might be possible to scratch some diamonds with other materials, such as boron nitride, the hardest diamonds can only be scratched by other diamonds and nanocrystalline diamond aggregates.

The hardness of diamond contributes to its suitability as a gemstone. Because it can only be scratched by other diamonds, it maintains its polish extremely well. Unlike many other gems, it is well-suited for daily wear because of its resistance to scratching—perhaps contributing to its popularity as the preferred gem in engagement or wedding rings, which are often worn every day.

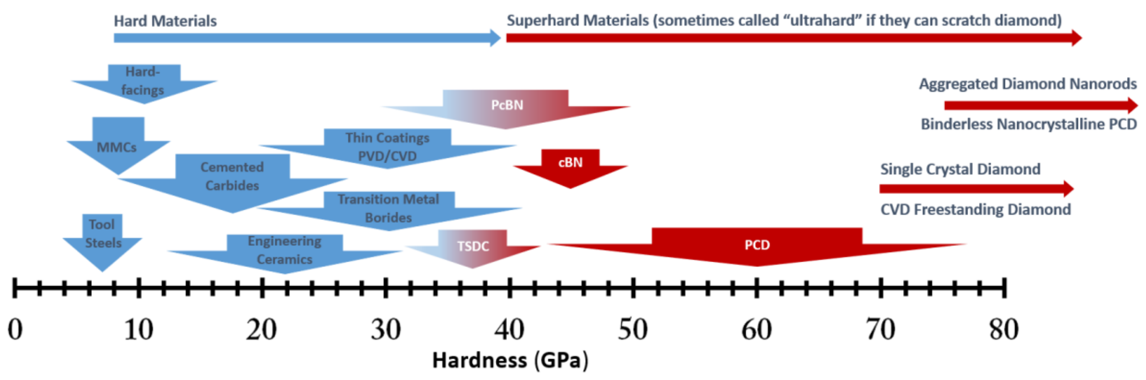


Figure 5: Materials hardness scale [3]

The hardest natural diamonds are found in the Copeton and Bingara fields, located in the New England area in New South Wales, Australia. These diamonds are generally small, perfect to semiperfect octahedra, and are used to polish other diamonds. As with all diamonds, hardness is associated with the crystal growth form, which in this case is single-stage crystal growth. Most other diamonds show more evidence of multiple growth stages. These stages can induce inclusions, flaws, and defect planes in the crystal lattice, all of which negatively affect their hardness. It is possible to treat regular diamonds under a combination of high pressure and high temperature to produce diamonds that are harder still. Of course, with the production of synthetic diamonds higher quality of product can obtained, as the higher uniformity of mechanical properties can be achieved [11].

2.4.2. Toughness

Somewhat related to hardness is another mechanical property *toughness*, which is the ability of material to absorb energy and plastically deform without fracturing. The toughness of natural diamond has been measured at 7.5–10 $MPa \cdot m^{1/2}$. This value is good compared to other ceramic materials, but poor compared to most engineering materials such as metal alloys, which typically exhibit fracture toughness of over 100 $MPa \cdot m^{1/2}$. As with any material, the macroscopic geometry of a diamond contributes to its resistance to breakage. Diamond has a defined cleavage plane and is therefore more fragile in some orientations than others. Diamond cutters can utilise this attribute to cleave some stones, which enables them to shape the diamond prior to grinding. "Impact toughness" is one of the main indexes to measure the quality of synthetic industrial diamonds [12].

2.4.3. Yield strength

Diamond has a compressive yield strength of 130–140 GPa. This exceptionally high value, higher than most alloys and ceramics, along with the hardness and transparency of diamond, it is the reason that diamond anvil cells are the main tool for high pressure experiments. These anvils have reached pressures of 600 GPa. Much higher pressures may be possible with nanocrystalline diamonds [13].

2.5. Surface properties

Diamonds are naturally lipophilic and hydrophobic, which means the diamonds' surface cannot be wetted by water. However, when diamond surfaces are chemically modified with certain ions, they are expected to become so hydrophilic that they can withhold multiple layers of water at human body temperature. This property can be used in creation of various diamond and diamond like carbon coatings, which could improve upon wear resistance of various implants in human body [14].

The surface of a diamond is partially oxidized. The oxidized surface can be reduced by heat treatment under hydrogen flow. This heat treatment partially removes oxygen-containing functional groups. But diamonds (sp^3C) are unstable against high temperature (above about 400 °C) under atmospheric pressure and tend to oxidize. The structure gradually changes into sp^2C above this temperature. Thus, diamonds should be reduced under this temperature.

2.6. Chemical properties

At room temperature, diamonds do not react with any chemical reagents including strong acids and bases.

In an atmosphere of pure oxygen, diamond has an ignition point that ranges from 690 °C to 840 °C; smaller crystals tend to burn more easily because of their higher specific surface. With the increase of temperature, it changes the colour from red to white and burns with a pale blue flame and continues to burn after the heat source is removed. By contrast in air, the combustion will cease as soon as the heat source is removed because the oxygen is diluted with nitrogen. A clear, flawless, transparent diamond is completely converted to carbon dioxide; any impurities will be left in a form of ash.

Diamond powder of an appropriate grain size around 50 μm burns with a shower of sparks after ignition with a flame. Consequently, pyrotechnic compositions based on synthetic diamond powder can be prepared. The resulting sparks are of the red-orange colour, comparable to charcoal, but show a very linear trajectory which is explained by their high density. Diamond also reacts with fluorine gas above about 700 °C [15].

3. DIAMOND PRODUCTION

3.1. Mining natural diamond

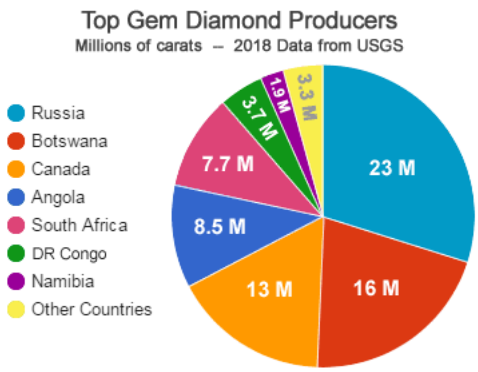
Most of the world's natural gem-quality diamonds are mined in low-income countries where citizens do not purchase a lot of diamond jewellery. The leading consumers of diamond jewellery include the United States, India, China, the European Union, Japan, Hong Kong, and the Middle East. The United States consumes over 40 % of the world's diamond jewellery, and the other areas listed together consume at least another 40 % of the world's diamond jewellery. None of these areas are important producers of natural gem-quality diamonds [16].

Figure 6: Natural diamond production countries of origin [16]

This map shows countries with at least 50,000 carats (1 carat = 0.2 grams) of natural gem-quality diamond production in 2018. The map clearly shows that natural diamond production occurs in many parts of the world where geological conditions for diamond formation and re-location to the top of the crust are favourable.

Since the 1870s, most of the world's gem-quality diamonds have been mined in Africa. The diamond production map above shows countries with at least 50,000 carats of natural gem-quality diamond production. The map illustrates that diamond production has spread to many parts of the world. Diamond production in Russia and Canada has grown rapidly, and these countries diversify the geographic distribution of natural gem-quality diamond production.

Seven countries have led the world in the production of gem-quality diamonds for over a decade. Russia, Botswana, Canada, Angola, South Africa, the Democratic Republic of the Congo, and Namibia have all been consistently producing over one million carats per year. Their consistent performance and dominance are shown in accompanying graph in figure 7.



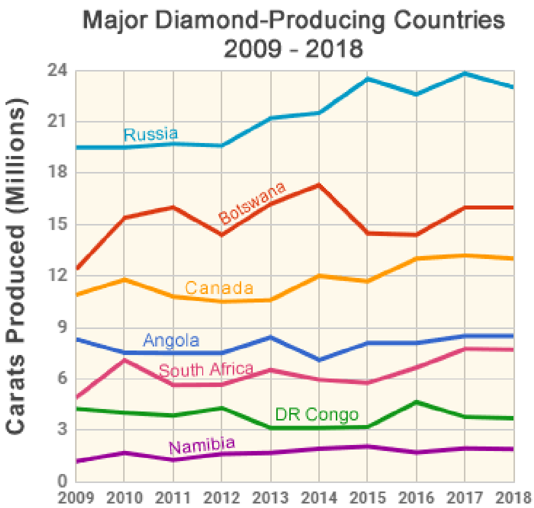


Figure 7: Leading diamond-producing countries [16]

Beyond the dominant producers, numerous countries produce less than one million carats per year, but are regular, consistent producers. Australia, Ghana, Guinea, Guyana, Lesotho, Sierra Leone, and Zimbabwe all produce over 100,000 carats of gem-quality diamonds per year and have averaged at least that much for the past decade. This production comes from smaller mechanized mines or an enormous number of artisanal workers in alluvial deposits [16]. Recent production is shown in the accompanying chart in figure 7.

Natural diamond is formed in volcanic regions at depths of around 150 kilometres, where the temperatures and pressures are sufficiently high to transform the carbon deposits into diamond.

Kimberlite pipes are created by deep-source volcanic eruptions. The magma inside the kimberlite pipes acts as an elevator, pushing the diamonds and other rocks and minerals through the mantle and crust in just a few hours. These eruptions were short, but quite intense with many times more power than volcanic eruptions that happen today.

The magma eventually cooled inside these kimberlite pipes, leaving behind conical veins of kimberlite rock that contain diamonds. Kimberlite is a bluish rock that diamond miners look for when seeking out new diamond deposits.

Figure 8: Extinct volcano with diamond deposit (a), diamond within kimberlite ore (b)

Diamonds may also be found in riverbeds, which are called alluvial diamond sites. These are diamonds that originate in kimberlite pipes but get moved by glacial activity. Glaciers and water can move diamonds thousands of miles from their original location. Today, most alluvial diamonds are found in Australia, Borneo, Brazil, Russia and several African countries.

Figure 9: Alluvial diamond extraction from rivers

3.2. Synthetic diamond production

The properties of natural diamonds are determined by the long and varied growth conditions, and therefore cannot be controlled. Without the control over shape, size and strength, no sustainable industrial products can be made. For that reason, industry turned to diamond synthesis in laboratory conditions. Today, the diamonds are being produced in vast factories in large quantities.

Synthetic diamond (also known as laboratory-grown diamond, or laboratory-created diamond) is diamond produced by a controlled process, as contrasted with natural diamond created by geological processes or imitation diamond made of non-diamond material that appears similar to diamond (for example, cubic zirconium).

Synthetic diamonds are also referred to as HPHT (high-pressure high-temperature) diamond or CVD (Chemical Vapour Deposition) diamond, after the two most common production methods. While the term synthetic may resonate in consumers' minds as a reminder of cheap and devoid-of-quality products, synthetic diamonds are made of the same material as natural diamonds—pure carbon, crystallized in an isotropic 3D form. The term synthetic only refers to diamonds not being mined in nature, rather produced by scientists and engineers. In industrial purposes they even have favourable properties compared to natural diamond. Figure 10 shows 2 images of synthetic diamonds under scanning electron microscope.

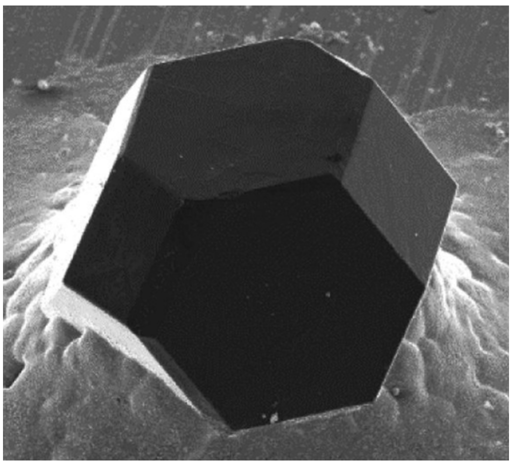


Figure 10: SEM pictures of synthetic diamond product, grain size of 1 mm

After the discovery of methods for diamond production and after exporting of related technologies to Asia (first Korea, then China), synthetic diamond production skyrocketed in the middle of 1990s. Prices started declining after the production volume has increased with each year, and diamond strength improved as the technology matured, as show in figure 11. Albeit, these figures are not 100 % correct, and should be taken with a grain of salt, relative values of price drop and toughness increase are relevant.

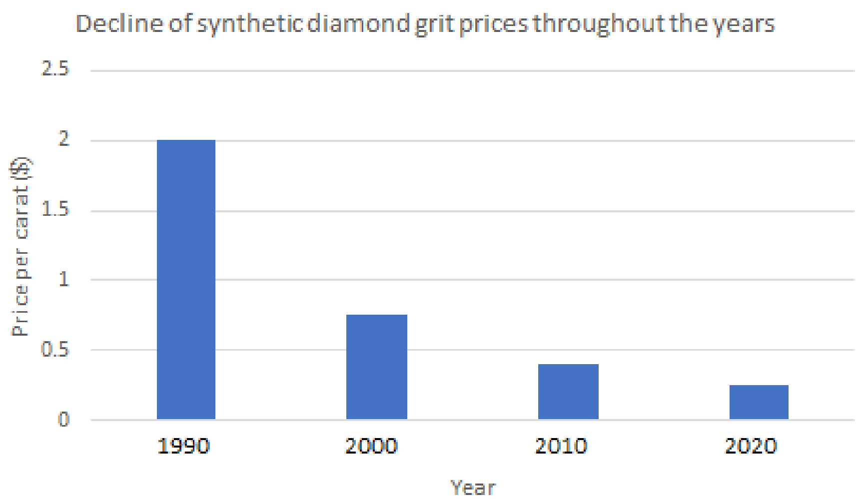


Figure 11: Price per carat throughout the years

In the span of only 10 years, prices halved, and today, prices are only 1/10 of those in 1985, adjusted for inflation. Today, almost all the diamonds used for industrial use are synthetic.

Term ‘Carat’ refers to the unit of mass traditionally used to measure diamond, equal to 0.2 grams. Interestingly, name carat comes from ancient time, before scales and units of mass were invented, and it comes from Carob tree. It was believed that seeds of Carob tree were uniform in their weight, which is equal to 0.2 grams.

Tight control over diamond sizing, shape and quality offers possibilities for production of broad range of diamond products, upon which modern industry can rely.

3.3. Belt press

In the high-pressure high-temperature method, there are two main press designs used to supply the pressure and temperature necessary to produce synthetic diamond: the belt press and the cubic press. The internal part of press is heated above 1400 °C and melts the solvent metal. The molten metal dissolves the high purity carbon source, either resulting in spontaneous nucleation of diamond crystals or further diamond growth around any diamond seeds which are in the mixture.

The original GE invention by Tracy Hall uses the belt press wherein the upper and lower anvils supply the pressure load to a cylindrical inner cell. This internal pressure is confined radially by a belt of pre-stressed steel bands. Anvils also serve as electrodes providing electric current (with high resistance) and therefore heat to the compressed cell. A variation of the belt press uses hydraulic pressure, rather than steel belts, to confine the internal pressure.

This type of press can grow many diamonds in one cycle, though much expertise is required to ensure optimum thermodynamic conditions in a large volume.
Belt presses are still used today, but they are built on a much larger scale than those of the original design [17].

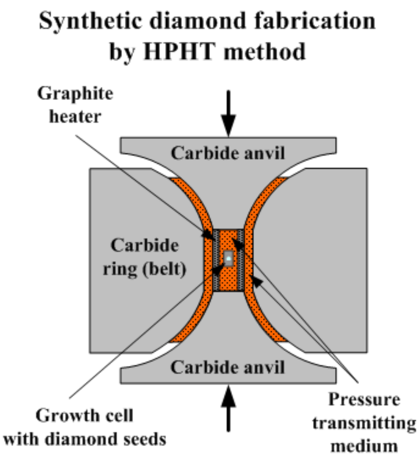


Figure 12: Belt press with inner workings [17]

3.4. Cubic diamond press

The second type of press design is the cubic press. A cubic press has six anvils which provide pressure simultaneously onto all faces of a cube-shaped volume. The first multi-anvil press design was a tetrahedral press, using four anvils to converge upon a tetrahedron-shaped volume. The cubic press was created shortly thereafter to increase the volume to which pressure could be applied. A cubic press is typically smaller than a belt press and can more rapidly achieve the pressure and temperature necessary to create synthetic diamond.

Cubic presses can be scaled up to larger volumes, but since most of production is done in countries with low labour and energy costs, small presses are predominant: the pressurized volume can be increased by using larger anvils, but this also increases the amount of force needed on the anvils to achieve the same pressure.

In the centre of a device, there is a ceramic cylindrical "synthesis capsule". Cell is placed into a cube of pressure-transmitting material, such as pyrophyllite ceramics, which is pressed by inner anvils made from cemented carbide (e.g., tungsten carbide or VK10 hard alloy). The outer cubic cavity is pressed by 6 steel outer anvils.

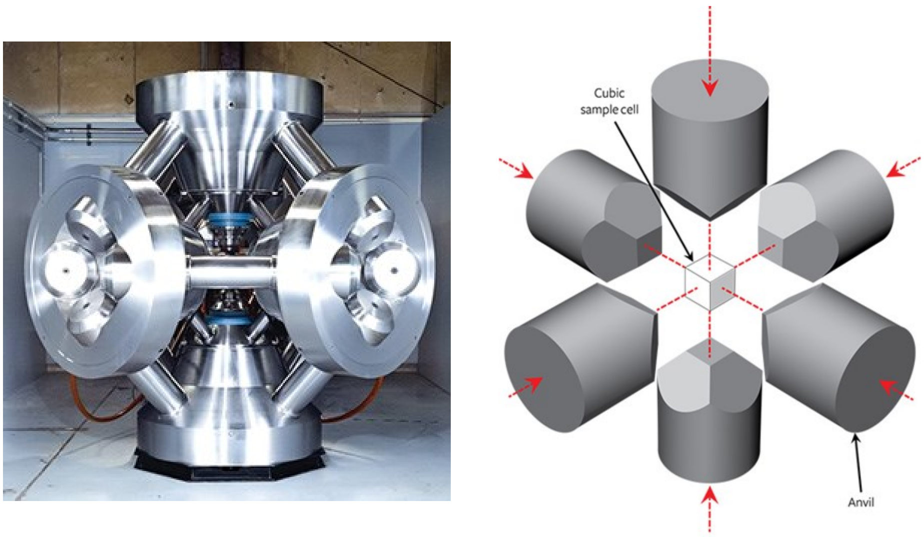


Figure 13: Cubic diamond press [18]

3.5. Chemical vapour deposition CVD

Chemical vapour deposition is a method by which diamond can be grown from a hydrocarbon gas mixture. Since the early 1980s, this method has been the subject of intensive worldwide research. Whereas the mass-production of high-quality diamond crystals make the HPHT process the more suitable choice for industrial applications, the flexibility and simplicity of CVD setups explain the popularity of CVD growth in laboratory research. The advantages of CVD diamond growth include the ability to grow diamond over large areas and on various substrates, and the fine control over the chemical impurities and thus properties of the diamond produced. Unlike HPHT, CVD process does not require high pressures, as the growth typically occurs at pressures under 27 kPa.

The CVD growth involves substrate preparation, feeding varying amounts of gases into a chamber and energizing them. The substrate preparation includes choosing an appropriate material (diamond itself is often the substrate); cleaning it, often with a diamond powder to abrade a non-diamond substrate; and optimizing the substrate temperature (about 800 °C) during the growth through a series of test runs. The gases always include a carbon source, typically methane, and hydrogen with a typical ratio of 1:99. Hydrogen is essential because it selectively etches off non-diamond carbon. The gases are ionized into chemically active radicals in the growth chamber using microwave power, hot filament, arc discharge, laser, electron beam, or other means. Diamonds coming out of the CVD process take the form of clear or grey wafers (depending on their purity), for use in abrasive applications (such as machining) and especially non-abrasive applications which exploit diamond's other extreme properties such as broad optical transparency and high thermal conductivity.

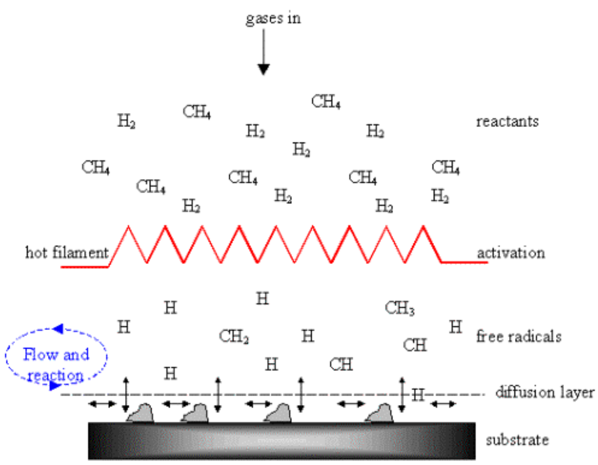


Figure 14: CVD methods of diamond coating [19]

4. DIAMONDS USE CASE SCENARIO

Hilti Corporation (Hilti Aktiengesellschaft or Hilti AG, also known as Hilti Group) is a Liechtenstein multinational company that develops, manufactures, and markets products for the construction industry, building maintenance, energy and manufacturing industries, mainly to the professional end-users. Its focus lies in development of fastening tools and systems, anchoring systems, fire protection systems, installation systems, measuring and detection tools (such as laser levels, range meters and line lasers), power tools (such as hammer drills, demolition hammers, diamond drills, cordless electric drills, heavy angle drills, power saws) and related software and services.

Business Unit Diamond in Hilti blends knowhow from classical segment manufacturing with fundamental material research and knowledge of diamonds accumulated through decades of breakthrough work. Besides diamond saw blades, one of the more popular products used by professionals around the world are diamond inserts for coring applications, used to drill concrete, rebar, masonry, etc. Each insert consists of a metal crown, on which metal-matrix segments containing diamond grit are welded or brazed. This process ensures optimal performance of the segment, regarding cutting speeds as well as suitable lifetime.

Figure 15: Hilti's diamond product range [20]

Hilti AG product portfolio uses synthetic diamond grit products (produced by high-pressure, high-temperature conversion from graphite) which come in various strengths and size bands. The size band of the product is selected according to whether the priority is surface finish (as in 80 µm diamond for polishing) or material removal rate (as in 600 µm diamond for drilling) [1]. Some of those could be observed in figure 16, where diamond snapshots from various tests were stitched together, to create a mosaic image.

The strength (or 'grade') of the product is then selected according to the characteristics of the base material to be cut and the drive parameters of the tool to be used.

Diamond grit works most effectively by maintaining sharp cutting edges. The optimal diamond strength should therefore be high enough to prevent premature fracture and thus shortening working life, without being so high that the particles polish to a smooth surface and lose their cutting ability.

Key to optimal performance of diamond tools lays in fine balancing of tool's life and cutting speed. In one hand, diamond mustn't wear to quickly but on the other hand it needs to wear fast enough.

Figure 16: Range of diamond quality

5. METHODS & EQUIPMENT USED FOR TESTING

5.1. Diamond characteristics and characterization

5.1.1. Diamond size, shape and distribution

Methods of measuring particle size in a diamond product vary from basic bulk size analysis to the examination of its size and shape distribution on a level of individual particles. The following subsections elaborate on methods that are being used for the purpose of this thesis, which are sieving, counting of particles per carat (per unit mass) and image analysis.

Figure 17: Diamond grit and sieves

Sieving is a well-established method of particles sorting according to size, in this case, diamond grit. The selection of appropriate sieves determines the upper and lower limit of sizes of particles in a specific size band. Diamond grit products are most commonly available in sizes defined by these upper and lower sieves (for example, US Mesh Size, FEPA size, DIN size), as shown in figure 19, and sieving equipment, which consists of sieves and vibratory tables, shown in figure 18. The procedure consists of using corresponding sieves, which are unique to each size, and then applying external force from a vibrating platform, to transfer energy to diamond particles, so they could pass through the sieve mesh.

As a size measurement technique, sieving indicates the mass percentage of particles within a specific size band. However simply defining the upper and lower sieves of a product's *as-sold* size, tends not to give accurate representation of the product. There are slight differences in sizing, such as the proportion of coarse to fine particles, and hence, the mean particle diameter.

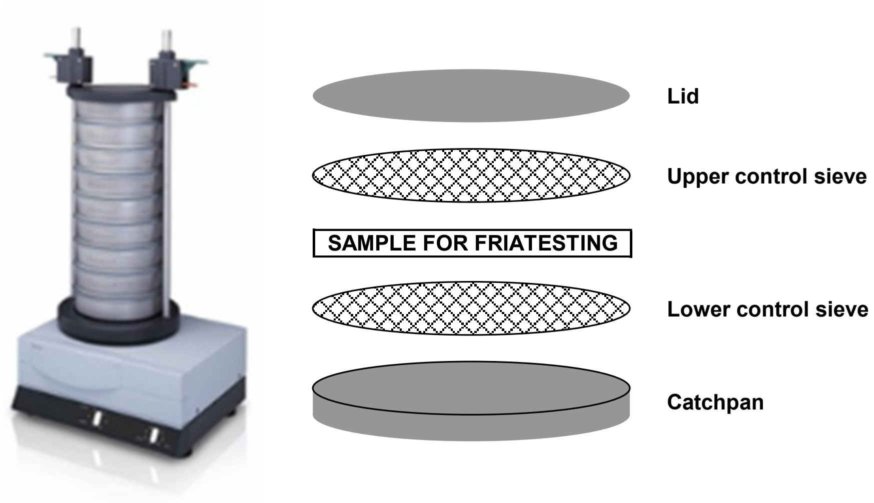


Figure 18: Sieving equipment, vibratory table and sieves

There are few different standards regarding grit size and sieve dimensions (China, International, WEC, USA, Japan, etc.) but most of them are rather comparable, as shown in figure 19.

CHINA		International			Western European Community		U.S.A		JAPAN	
GB/T6406-1996		ISO6106-1979			FEPA-1997		ANSI B74.16-1971 (R1980)		JIS4130-1982	
Grit Size	Dimension	Grit Size I	Grit Size II	Dimension	Grit Size	Dimension	Grit Size	Dimension	Grit Size	Dimension
16/18	1180/1000	1181	16/18	1180/1000	D1180	1180/1000	16/18	1180/1000	16/18	1180/1000
18/20	1000/850	1001	18/20	1000/850	D1001	1000/850	18/20	1000/850	18/20	1000/850
20/25	850/710	851	-	850/710	D851	850/710	20/30	850/600	20/30	850/600
25/30	710/600	711	-	710/600	D711	710/600				
30/35	600/500	601	-	600/500	D601	600/500	30/40	600/425	30/40	600/425
35/40	500/425	501	-	500/425	D501	500/425				
40/45	425/355	426	-	425/355	D425	425/355	40/50	425/300	40/50	425/300
45/50	355/300	356	-	355/300	D356	355/300				
50/60	300/250	301	50/60	300/250	D301	300/250	50/60	300/250	50/60	300/250
60/70	250/212	251	-	250/212	D251	250/212	60/80	250/180	60/80	250/180
70/80	212/180	213	-	212/180	D213	212/180				
80/100	180/150	181	80/100	180/150	D181	180/150	80/100	180/150	80/100	180/150

Figure 19: Diamond grit norms

After sieving, PPC (Particles Per Carat) analysis is next on the list. With these two methods, easy control of number of particles in any product which the diamonds are a part of can be achieved.

Particle counting machine is shown in figure 20. It is produced by company called Metha Tools, model - Data Count Jr. The operational principle is simple. After weighing, diamonds are put onto a particle counting machine, which using strong vibration motor propels particles up stream, until particles fall through an aperture. In this aperture, two laser beams are located. Upon beam disruption, a diamond is counted. Simply dividing the number of particles counted by the mass of those particles (in carats), give the particles per carat result. PPC measurement is highly repeatable and reproducible method.

Figure 20: Particle counting machine used in experiments

Sieving results simply state the amount of diamond between two limits, while the PPC is a measurement related to average particle size. Further information about particle sizing can be obtained by optical image analysis. From size measurements on individual particles, the full form of the particle size distribution can be understood.

Optical image analysis is an automated method (figure 21), which calculates relevant size information. Image analysis process starts with taking a diamond sample that is representative of whole diamond group by a scoop and feeding it into circular vibratory pathway. Diamonds are being moved onto a rotating disc, to which mounted camera is pointed. Diamonds are encountering rotating disc on which snapshots of individual diamonds are taken, and all the relevant particle size and shape parameters are calculated. Test setup used in this thesis is called Diainspect-P, and it was produced by Vollstädt Diamant GmbH company.

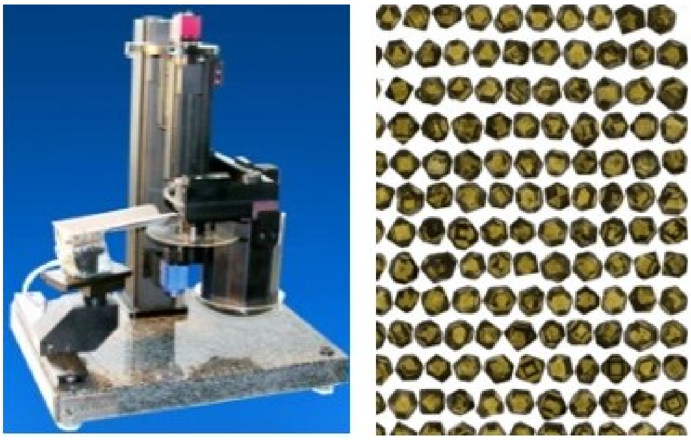
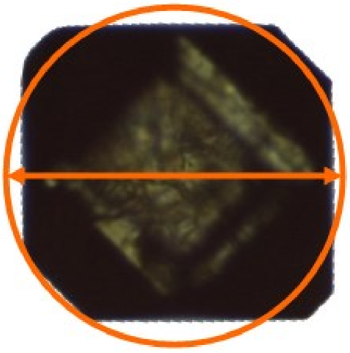


Figure 21: Optical image analysis with example of captured diamonds [21]

Although upper and lower sieve size are determining size band, there are still uncertainties in size distribution in this size band. That's why there is a strong emphasis on image analysis and parameters described in following section. One of the most important size parameters for diamond abrasives is equivalent circle diameter.



$$\text{Equivalent circle diameter} = \sqrt{\frac{4 \times \text{area}}{\pi}}$$

Figure 22: Equivalent circle diameter

The *equivalent circle diameter* is the diameter of a circle with the same projected area as the particle. The image analysis software will measure the projected area of the diamond particle, fit the particle outline to a circle and then calculate the particle diameter.

As seen in figure 23, even within the same diamond size, there is a valid probability that particle size distribution can be different.

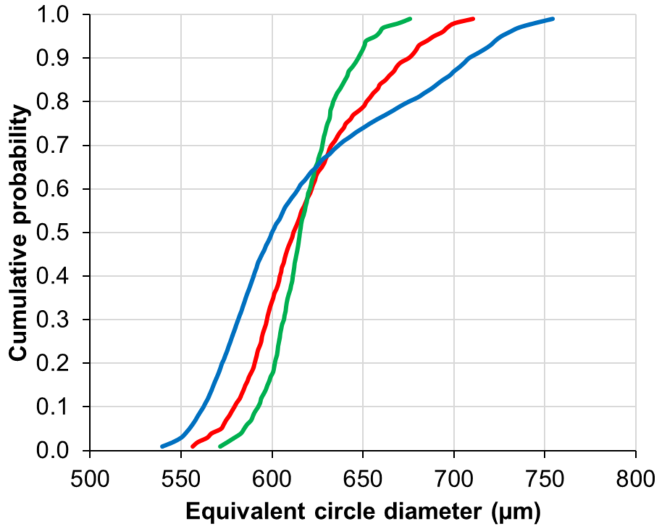


Figure 23: Equivalent circle diameter distributions of three 30/35 mesh diamond samples

By taking a measurement of the equivalent circle diameter of each particle, the particle size distribution can be understood. Figure 23 shows an example of the particle size distributions of three different diamond samples in size 30/35 mesh. They fully conform to the 30/35 sieving standard, being 100% *on-size*, and they have the same average particle size and therefore the same PPC. Average equivalent circle diameters for diamond products in colour red, green and blue are 0.619 mm, 0.617 mm and 0.619 mm, respectively. One could conclude, that these products are identical, but as it's shown, these products have different widths to their particle size distributions.

This highlights the importance of information that image analysis can provide that sieving and PPC alone do not.

In addition to several different parameters for measuring particle size, image analysis can be used for measuring characteristics of particle shape such as elongation, circularity and roughness, etc. One of the more important shape parameters used in this thesis is ellipticity.

Ellipticity, a measurement of particle elongation, is the ratio of the major and minor axes of the particle's Legendre ellipse (an ellipse of the same geometrical moment of inertia, shown in green in figure 24). If the particle shape has rotational symmetry (such as a square, hexagon, octagon, etc.) then the Legendre ellipse is a circle, and the ellipticity value is 1. Higher ellipticity values indicate more elongated objects.

$$\text{Ellipticity} = \frac{\text{major axis of Legendre ellipse}}{\text{min or axis of Legendre ellipse}}$$

Figure 24: Ellipticity and Legendre ellipse

Usually, lower-grade (lower strength) diamonds are very elongated and higher-grade (higher strength) diamonds are less elongated.

Shown in figure 25, cumulative probability of ellipticity shows distribution of diamond shape, which correlates with diamond strength. Higher diamond quality tends to have ellipticity factor distribution floating as close as possible to 1. Also, in the same chart difference between three diamond products, which are same in size but of different quality grades, can be observed. Product A represents premium grade diamond, product B high-end diamond and product C mid-range diamond quality.

Ellipticity of product A is somewhat closer to 1, which could in part explain better properties of product A in comparison to B and C.

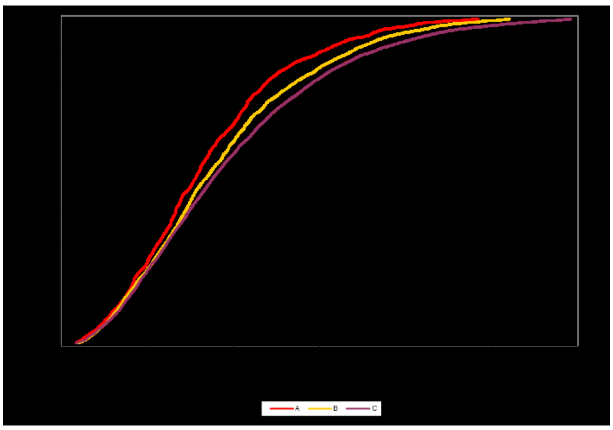


Figure 25: Probability distribution of ellipticity

Image analysis methods offer key insights into the diamond shape distribution in a form of a report, as shown in figure 26.

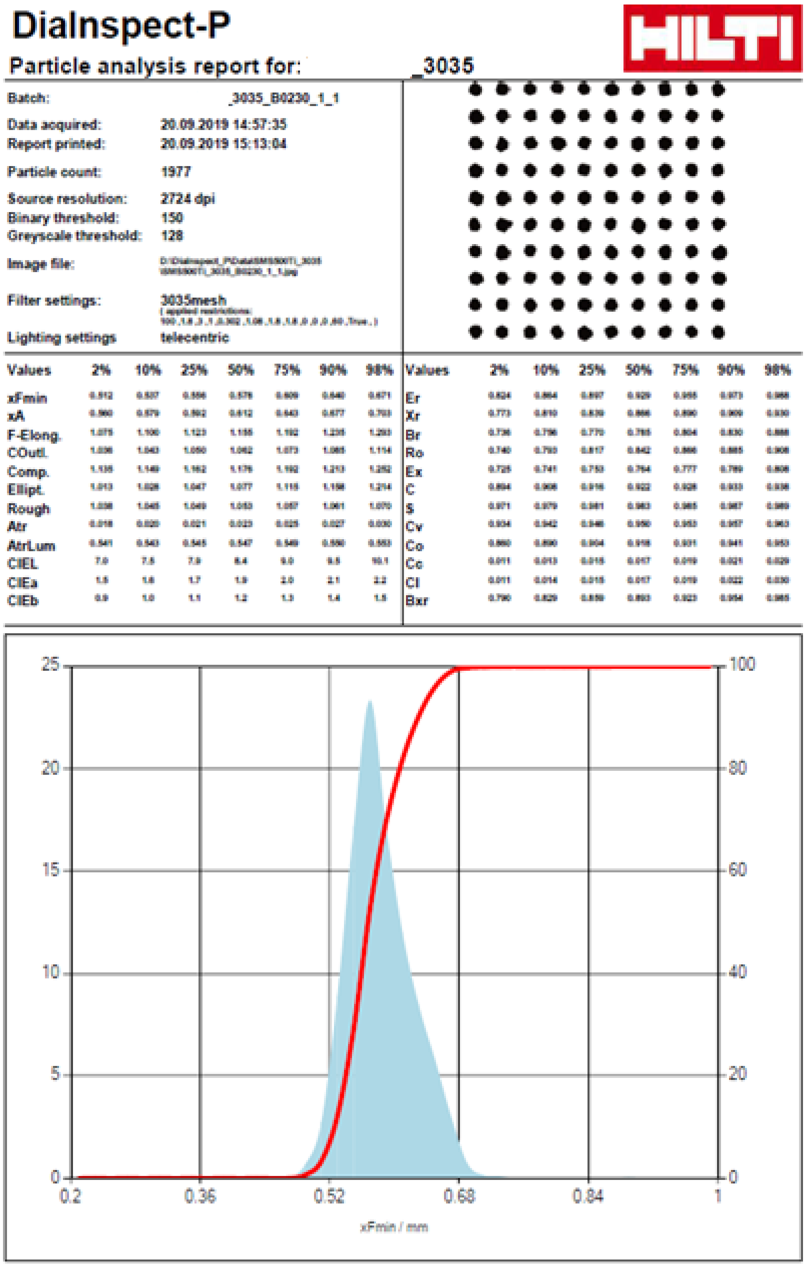


Figure 26: Image analysis diamond shape output

In a few minutes of test time the image analysis system gives a wide range of information on the size and shape of each particle.

In conjunction with sieving and PPC, this method gives complete characterization of tested diamond sample; size band, number of particles and shape distribution.

5.1.2. Diamond strength

Laboratory measurement of particle strength is common yet extremely slow method of diamond characterization. In some instances, it is a requirement, as the strength of a diamond grit product determines its suitability for use in the processing of workpiece materials. The two main methods of measuring grit strength are friability (impact) testing and single particle (compressive) strength testing. Whilst their principles of operation are quite different, with careful experimental design and sound interpretation of results, the two methods can provide complementary information on product's strength. In this section, compressive strength testing experiments are described.

Compressive strength testing of commonly used diamond sizes such as 30/35 mesh (600µm) can be performed using specialised commercially available equipment. However, in this project there was a need to study much larger diamond, up to 12/14 mesh (1.7mm), for which no commercially available equipment is suitable. A new test method using a hydraulic press 'universal tester' has been developed.

Experiments were done using Zwick Roell BZ1-MM 200 kN hydraulic press equipped with 250 kN force sensor, which is mounted above the test sample, in line with piston which applies force. Individual diamond particles were placed between plates made of polycrystalline diamond (PCD), which is hard and tough enough so that it doesn't deform or break (unlike tungsten carbide counterparts) while testing single crystal diamonds. Images of the force sensor and PCD plates are shown in figure 27, with force sensor specification shown in table 1, on the next page.

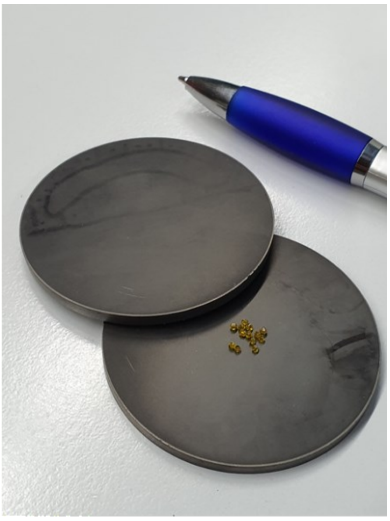


Figure 27: Hydraulic press used for diamond crushing with PCD plates

Table 1: Force sensor specification

Kraftaufnehmer; Fmax *Load cell; Fmax*	Typ *Type*	Hersteller *Manufacturer*	Hersteller-Nr. *Manufact.-No.*	Werk-Nr. *Serial-No.*
250 kN	Z12	HBM	C93112	109559

All the tests were conducted with fixed parameters, a pre-load force of 20 N and speed of 0.1 mm/min. The more particles are crushed the better the accuracy of the results. But, with this highly manual method only about 10 particles per hour could be crushed to account for large spread of results, as shown in figure 28.

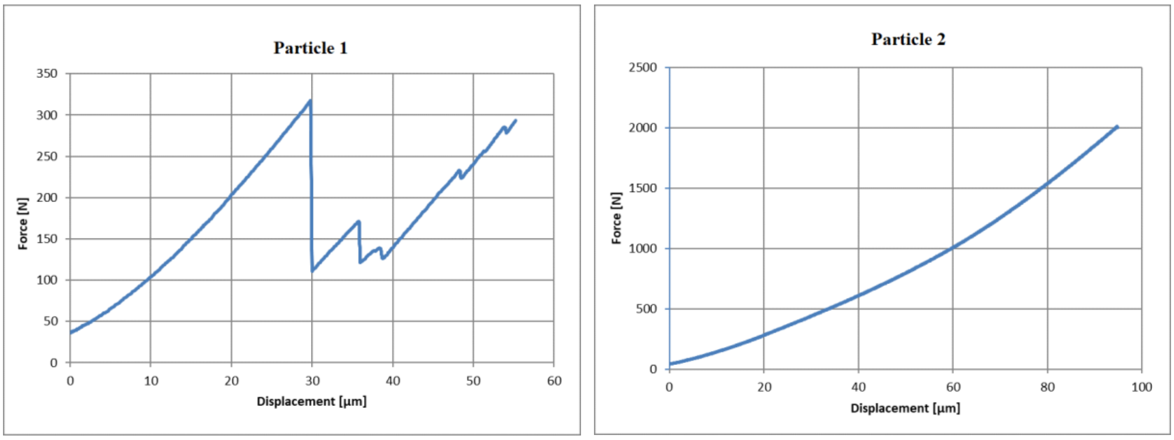


Figure 28: Comparison between different particles

After pre-load force of 20 N is applied, the system starts the testing procedure with the speed of 0.1 mm/min.

As shown in figure 28, particle 1 is loading linearly until force exceeds 320 N, and first cracks start to form. These cracks compromise particles compressive strength and propagate every time more force is applied. Formation of cracks have a distinct form in force/displacement charts, as abrupt decline of applied force.

Particle 2 is completely opposite in its behaviour, loading nominally without crack formation until force exceeds 2000 N, when it fails and breaks in a single event. These particles are taken from the same batch of diamonds, and in some instances could give massive spread of results, as shown in figure 29, with statistical information presented in table 2.

These differences are a function of positioning of particles between PCD anvils, particles shape, residual stress from diamond manufacturing, and possible microstructural irregularities in diamonds crystal lattice.

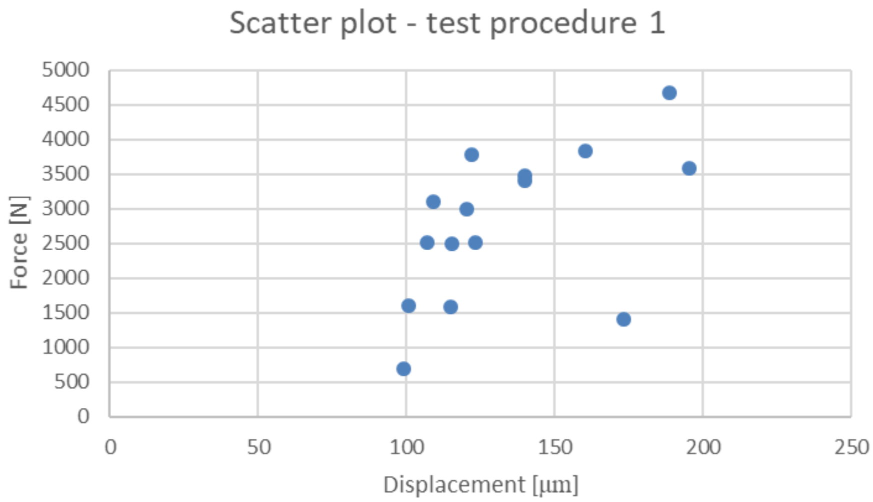


Figure 29: Result scatter in one test group

Table 2: Statistical data regarding test procedure 1

	F, N	Displacement, µm
Mean value	2773.718	133.983
Standard deviation	1089.044	31.540
Variance	39.263	23.540

After each test is conducted, the accompanying software creates a summary test sheet as shown in figure 30. In this case, the sheet shows the fracture forces and displacements of the 12 particles tested, together with their force-displacement curves.

Zwick / Roell

Pressure tests large diamonds

Überschrift	: Pressure tests large diamonds	Probenentnahme	:	customer
Kunde	:	Probentyp	:	Diamond
Auftrags-Nr.	: TWU	Prüfer	:	Matija Pisk
Art und Bezeichnung	: pressure test	Maschinendaten	:	UPM Zwick & Roell 250kN
Werkstoff	: Diamond			force-sensor: 250kN

Vorkraft : 20 N
Prüfgeschwindigkeit : 0.1 mm/min

Prüfergebnisse:

Legende	Nr	Probenbezeichnung	F_{max} N	displacement in um µm
	1	) 12-14 Hilti-1 newb_1	4885.41	170.95
	2	) 12-14 Hilti-1 newb_2	6636.60	234.38
	3	) 12-14 Hilti-1 newb_3	5749.38	173.36
	4	) 12-14 Hilti-1 newb_4	4963.68	159.36
	5	) 12-14 Hilti-1 newb_5	4589.61	158.96
	6	) 12-14 Hilti-1 newb_6	5073.58	176.82
	7	) 12-14 Hilti-1 newb_7	5441.58	170.47
	8	) 12-14 Hilti-1 newb_8	8461.51	201.29
	9	) 12-14 Hilti-1 newb_9	4383.46	172.49
	10	12-14 Hilti-1 newb_10	5345.19	181.49
	11	12-14 Hilti-1 newb_11	8301.75	218.48
	12	12-14 Hilti-1 newb_12	2881.46	97.60

Seriengrafik:

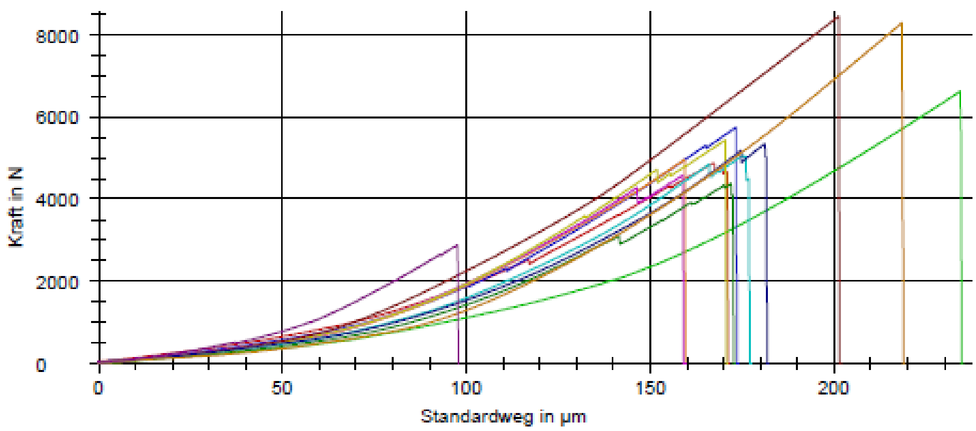


Figure 30: Force/depth diagram after conducted tests on hydraulic press

5.1.3. Diamond toughness

Friability testing, also known as friatesting, toughness testing and dynamic strength testing, measures a diamond sample's resistance to impact. The development of a technique for measuring of the impact strength of diamond grits began in the 1950s at De Beers' Diamond Research Laboratory, while the first friatester was announced in the following decade [4]. Since then there have been numerous modifications and different versions. There are now several different friatester designs, either commercially available or proprietary to diamond manufacturers. Hilti AG uses the commercially available ReTek friatester produced by company Vollstädt Diamant, shown in figure 31.

Figure 31: Friability tester from ReTek company with capsule [23]

Every friatesting follows the same operating procedure which consists of pre-sieving and sizing of the initial sample, followed by controlled crushing of the sample by a steel ball inside an oscillating capsule. After the test is conducted, content of the capsule is sieved through a corresponding sieve set After weighing (figure 32.) and some simple calculations, toughness index can be obtained, which offers ranking of sample strength.

This operating procedure was also followed for testing purposes of this thesis.

Figure 32: Mettler AT200 Scale used in experiments

All the tests were carried out using 1000 cycles. Friability tester can be adjusted in increments of 100 cycles, and it is crucial to compare results which were carried out using the same cycle number. Each test requires a fresh steel ball, because even in that short time of a single testing, steel ball gets worn down from impacting the diamond. Each steel ball used in this procedure has a diameter of 7.9375 mm (5/16”).

The friatesting procedure from start to finish is slow, but some tasks can be performed in parallel, which can speed up the whole procedure. Also, operator could influence the results, so consecutive testing procedures should be carried out by a single operator. Furthermore, as the capsule racks up test cycles, its inner surface slowly but surely gets worned down by diamonds abrasive nature.

That’s why after some time, baseline tests are carried out to account for any drift in results, coming from the capsule itself. Until today, there are no clear international standards on friatesting. Each company could have a different approach, so the results are sometimes incomparable. In-house testing ensures that the results are comparable within the company and can be used with higher degree of confidence in product planning and manufacturing. Regardless, sieves that are being used are controlled, and unique to each size band.

There are sieve sets needed in friatesting, sieves for pre-sieving which are shown in table 3, and breakdown sieves which are used to capture finer residue particle, as shown in table 4. Sieves standardized by European producers of abrasives (FEPA) are also presented in these tables.

Table 3: Sieve specification for pre-sieving

US mesh size	Equivalent FEPA size designation	Upper control sieve size (µm)	Lower control sieve size (µm)
20/25	D851	915	710
25/30	D711	770	600
30/35	D601	645	505
35/40	D501	541	425
40/45	D426	455	360
45/50	D356	384	302
50/60	D301	322	255
60/70	D251	271	213

Table 4: Sieve specification for post-test sieving

US mesh size	Equivalent FEPA size designation	Friability breakdown sieve size (µm)
20/25	D851	600
25/30	D711	505
30/35	D601	425
35/40	D501	360
40/45	D426	302
45/50	D356	255
50/60	D301	213
60/70	D251	181

After whole testing procedure is completed, toughness (short TI) index calculation is done using formula as shown (1). Some examples of weighing and toughness indexes are presented in figure 33.

$$TI = \frac{residue, g}{initial\ weight, g} * 100 \tag{1}$$

Product	Test cycles	Initial weight, g	Residue, g	Toughness index
A 1820	1000	0.3998	0.3643	90
B 1820	1000	0.3988	0.3406	87
C 1820	1000	0.3991	0.34	83
A 1618	1000	0.4002	0.3701	91
B 1618	1000	0.3989	0.3587	89
C 1618	1000	0.3991	0.3119	80

Figure 33: Examples of toughness indexes

Friability test error, for conventional finer diamond grit is around ± 0.1 %. Moving to the coarser diamond grit, where there are far fewer particles in the capsule, this error can increase.

5.2. Wear category and mechanisms

As in any multi-body wear system, there are number of wear mechanisms that occur in any moment. Utilising tribological principles, we can identify different mechanisms and approaches on how to solve unwanted wear. Tribology is the scientific discipline which deals with interacting surfaces in relative motion. It includes the study, correlation and application of the principles of friction, lubrication and wear, used in different fields such as mechanical engineering, biology, etc. Different tribological mechanisms can have different effects. Two of the most dominant are:

1.) Abrasion - The abrasive wear consists of the cutting effort of harder surfaces that act on softer surfaces and can be caused either by the roughness as tips cut off the material against which they rub (two-body abrasive wear), or from particles of harder material that interpose between two surfaces in relative motion (three-body abrasive wear).

2.) Adhesion - The problem occurs through micro-welding of elements in contact. If a shearing force is applied in the contact area, it may be possible to detach a small part of the weaker material, due to its adhesion to the harder surface.

As shown in figure 34, there are six distinct wear states that arose from diamond appraisal, which are characteristically found in diamond wear.

Figure 34: Diamond wear states and particle lifecycle

Diamond appraisal is a method of ranking of diamond particles where appraiser inspects each individual particle and ranks it according to a predefined ranking system. From 6 wear states, there are also distinct separation of active and inactive particles.

1.) Emerging – diamond protrudes out of bond surface but is inactive.
2.) Wear flat (polished) – diamond has been flattened from wear, but still active.
3.) Wear flat and rough – diamond is still active.
4.) Rough – expected and preferred wear profile, active diamond.
5.) Cleaved – high load on individual diamond, inactive.
6.) Deep hole (pull-out) – bond retention is insufficient.

There are different variables that go into diamond wear prediction, which includes diamond size, quality and concentration, bond properties, power and torque delivered by machine, properties of concrete, etc. As shown in figure 35, there are 3 distinct wear profiles that can be observed.

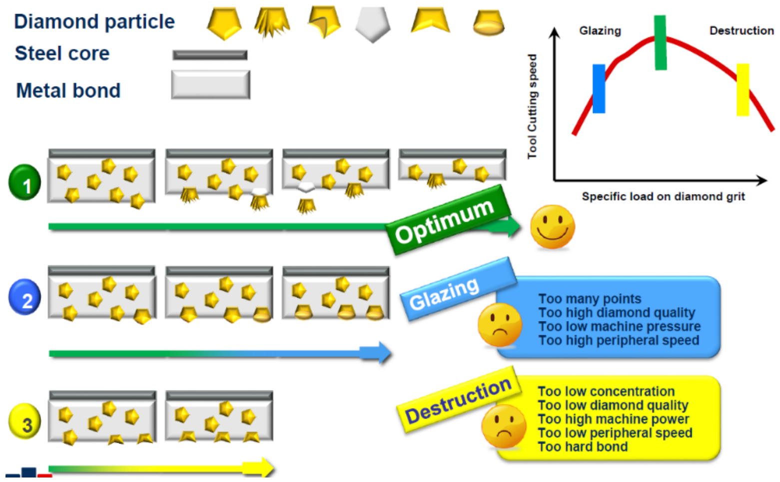


Figure 35: Optimising diamond wear profile

Profile no. 1 is optimal with ideal ratio of lost, dulled diamonds and uncovering of fresh sharp ones. Profile no. 2 shows too high of a retention rate, glazing diamonds without uncovering of fresh ones. Profile no. 3 shows complete destruction of the diamonds, which could be avoided using higher strength diamonds. A steady wear state regime of type 1 allows for optimal performance (speed/lifetime balance) of the diamond insert.

5.3. Concrete type and differences

Concrete is a heterogenous composite material composed of fine and coarse aggregate bonded together with a fluid cement (cement paste) that hardens over time.

Most frequently in the past a lime-based cement binder, such as lime putty sometimes mixed with other hydraulic cements, such as calcium aluminate or calcium silicate (known as Portland cement) was used.

Many other non-cementious types of concrete exist with different methods of binding aggregate, including asphalt concrete with a bitumen binder, which is frequently used for road surfaces, and polymer concretes that use polymers as a binder.

Concrete core sample, obtained after conducted coring test, is shown in figure 36.

Figure 36: Concrete core sample taken for testing

For research purposes, Hilti is trying to emulate most of the occurring concrete types with its counterparts. These blocks are specifically made to order, and have different properties, like aggregate size and hardness, different ratios of aggregate/binder and therefore, different abrasivity levels. Different concrete properties have a large impact in diamond insert behaviour, from the standpoint of lifetime and cutting speed.

If the concrete is less abrasive, a diamond/bond combination which allows for faster diamond wear and avoids diamond polishing and premature catastrophic insert wear is used.

On the other hand, if the concrete is more abrasive, then diamond/bond combinations which have better diamond retention and stronger diamonds are used.

Basically, inserts are tailor made to specific concrete type and application, offering the best combination of tool life and cutting speeds in any working condition.

As mentioned before, there is a rule of thumb when deciding which combination of bond and diamonds should be used.

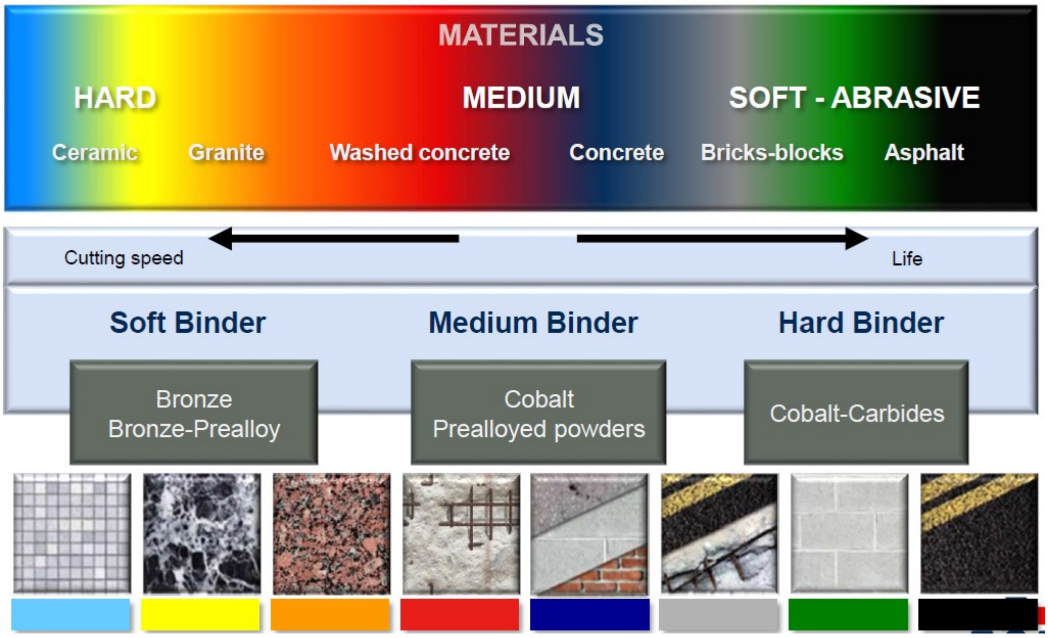


Figure 37: Binder hardness selection vs. abrasivity of material

As show in figure 37, there are a few possibilities to choose from. If conditions require cutting of hard and non-abrasive materials, a soft or medium binder, based on bronze or cobalt alloys can be used. This ensures high cutting speeds, while low abrasivity guarantees long insert life.

If conditions require cutting of soft and abrasive materials, medium or hard binder like cobalt-carbides can be used. A hard binder resists the abrasivity of the material being cut, therefore ensuring longer lifetime, while soft nature guarantees high cutting speeds.

This interplay of material hardness and abrasivity, albeit sometimes counter intuitive, governs the direction of insert development.

6. EXPERIMENTAL RESEARCH

Experimental part of this thesis consists of two chapters, which are different in their nature. First, experimental part contains academic approach in defining of a test procedure that can be applied on broad range of products.

Second - failure mode analysis, represents a method of discovering a problem in diamond tool working life in order to identify exact failure mode and using that insight in improvement of key properties.

1.) Diamond strength testing
2.) Failure mode analysis

6.1. Friability testing & Image Analysis

As explained in chapter 5.1.3, friability testing is a test method that indicates the toughness of a diamond product.
Many diamond production companies carry out their own friability testing as a measure of product design and quality control which is important when devising a product portfolio. For companies like Hilti AG, which are the primary users of these diamonds, friability testing can be extremely useful as a mean of internal quality control, as well as for comparing products from different diamond companies.

Usually, tests are conducted using the testing capsules of determined quality and properties. To account for any drift in results, after 50,000 cycles baseline measurement (i.e. referencing) is performed, as capsules properties degrades over time. Doing baseline measurements, we can exclude any influence from properties change of test capsule, on the results.
Test procedure consists of putting 2 carats (0.4 g) of diamond in a capsule with a small steel ball, which then from piston movement transfers the momentum of movement of the capsule, to the diamonds. Usually, for finer diamond grades, weight tolerances of 0.4 g ± 0.5 % (i.e., 0.398 to 0.402 g) are applied, but in the case of coarser larger grit, individual diamond are heavier than lower and upper limit of tolerance, so this tolerance does not apply in that case.

Regardless, it is optimal to weigh as close as possible to 2 carats, to ensure fair comparison between samples.

This process crushes some of the diamonds, and then through the ratio of intact and crushed diamonds, toughness index can be calculated.
As shown in figure 38, particle sizes are most commonly given by sorting them into different half sizes.

US mesh size	**FEPA designation**	***Oversize limiting sieve (µm)***	**Upper control sieve (µm)**	**Lower control sieve (µm)**	***Undersize limiting sieve (µm)***
10/12	-	*3010*	2170	1700	*1180*
12/14	-	*2580*	1830	1400	*1010*
14/16	-	*2170*	1520	1180	*850*
16/18	D1181	*1830*	1280	1010	*710*
18/20	D1001	*1520*	1080	850	*600*
20/25	D851	*1280*	915	710	*505*
25/30	D711	*1080*	770	600	*425*
30/35	D601	*915*	645	505	*360*
35/40	D501	*770*	541	425	*302*
40/45	D425	*645*	455	360	*255*
45/50	D352	*541*	384	302	*213*
50/60	D301	*455*	322	255	*181*
60/70	D251	*384*	271	213	*151*
70/80	D213	*322*	227	181	*127*

Figure 38: Relation of mesh sizes and voids in sieve meshing

For example, size 30/35 will have particle size ranging from 0.505 to 0.645 mm, with some particles under or oversize.
Size 30/35 is one of sizes most commonly used in products, and therefore in properties testing. Most commonly used size ranges are from mesh 20 (0.845 mm) to mesh 40 (0.425 mm). These sizes are well standardized through friability testing with set parameters like number of cycles, steel ball diameter and number of carats used.

Friability testing is less commonly used in sizes 18 mesh and above, and there is less experience in the diamond industry of how to test these large particles. Knowing the test procedure for finer sizes, same procedure was carried out for coarser sizes, and viability of friability testing in those instances were put to a test.

As shown in figure 39, the capsule that is used for friability testing is made by the same company which produces the friability tester used at Hilti. The capsule consists of 3 parts:

- main body of the capsule (a),
- plug that ensures tight fit with capsules sides and prevents any diamonds and dust from escaping during testing (b),
- a lid which holds everything in place (c).

Bottom of the capsule is threaded, and there is a hexagonal pattern on the other side, with which operator can manipulate the capsule with special tool and thread it into place, onto a piston.

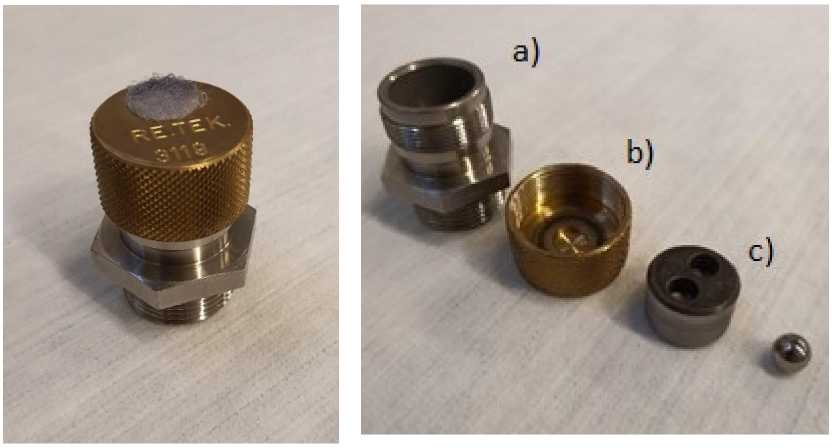


Figure 39: Capsule 3319 pictures, assembled and disassembled

Test cycles were kept constant at 1000 cycles per test. Also, new steel ball was used for each test.

Table 5: Testing procedure

Step 1	Sieve selection upon diamond size
Step 2	Select number of cycles (1000-testing, 2000-referencing)
Step 3	After friatesting, sieving of residue
Step 4	Residue weighing
Step 5	Toughness index calculation

Difference between testing and referencing is that referencing relies upon laboratory tested diamonds, which have a role of an etalon. Other difference is that in referencing, 2000 test cycles are used, instead of 1000 in normal testing.

When testing finer diamond grits, nominal trend can be observed, as shown in figure 40, which suggest that highest-end product ranks with highest toughness index, and lowest-end product ranks with lowest toughness index, shown in upper row. Premise of this experimental part would be to find out if the same holds true for coarser diamond grit, shown in lower row.

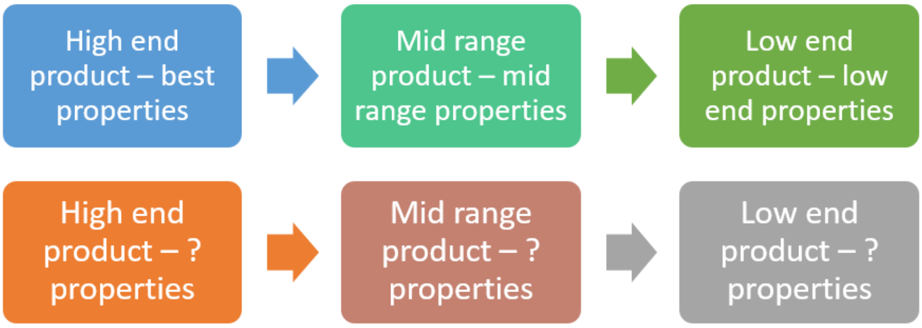


Figure 40: Diamond ranking, finer and coarser sizes

Test was conducted using different diamond grades (qualities) of the same sizes as shown in table 6, with a goal of comparing toughness indexes between sizes and grades.

Table 6: Testing samples used in friability DOE

Type	Size	Capsule	Size	Capsule	Size	Capsule	Size	Capsule
A	1214	1	1416	1	1618	1	1820	1
A	1214	2	1416	2	1618	2	1820	2
A	1214	3	1416	3	1618	3	1820	3
B	1214	1	1416	1	1618	1	1820	1
B	1214	2	1416	2	1618	2	1820	2
B	1214	3	1416	3	1618	3	1820	3
C	1214	1	1416	1	1618	1	1820	1
C	1214	2	1416	2	1618	2	1820	2
C	1214	3	1416	3	1618	3	1820	3

Experiments were carried out using the same capsule to minimise any result variation from capsule change. Baseline referencing of test capsule was performed regularly. As show in figure 39, standard test capsule was used. 2 carats of each sample were placed into the capsule alongside with steel ball. After assembling the capsule, capsule is threaded into position and testing procedure can be started.

As a baseline for this friability testing, observations were made on more frequently used sizes, 25/30, 30/35 and 35/40, shown in table 7.

Table 7: Results of initial friability testing

Product	Test cycles	Toughness index
A 2530	1000	89.94
B 2530	1000	82.91
C 2530	1000	78.02
A 3035	1000	91.10
B 3035	1000	90.41
C 3035	1000	87.52
A 3540	1000	94.03
B 3540	1000	93.05
C 3540	1000	91.43

As shown in table 8, a clear distinction between different product grades can be observed, as toughness index declines with lessening of product quality (A - highest grade, C - lowest grade). An expected ranking system is formed, witch directly correlates to diamond pricing and toughness index.

When moving to larger size grit as shown in table 8, with sizes like 16/18 and 18/20, we can still observe the same ranking order, diamond grade A having a higher toughness index and ranking, in comparison with grades B and C.

Table 8: Results of further friability testing

Product	Test cycles	Initial 1 (g)	Residue 1 (g)	Initial 2 (g)	Residue 2 (g)	Initial 3 (g)	Residue 3 (g)	TI Capsule 1	TI Capsule 2	TI Capsule 3	Toughness Index
A 1820	1000	0.4002	0.3673	0.3994	0.3492	0.3997	0.3064	91.78	87.43	76.66	82.0
B 1820	1000	0.4000	0.3283	0.3999	0.3498	0.4000	0.3366	82.08	87.47	84.15	85.8
C 1820	1000	0.3996	0.3182	0.3997	0.3177	0.4001	0.3265	79.63	79.48	81.60	80.5
A 1618	1000	0.4005	0.3643	0.3996	0.3581	0.4005	0.3583	90.96	89.61	89.46	89.5
B 1618	1000	0.4008	0.3514	0.4005	0.3491	0.4002	0.3389	87.67	87.17	84.68	85.9
C 1618	1000	0.4007	0.3145	0.4006	0.3108	0.4007	0.3033	78.49	77.58	75.69	76.6
A 1820	1000	0.6001	0.5512	0.5999	0.5568	0.6003	0.5598	91.85	92.82	93.25	93.0
B 1820	1000	0.5997	0.5475	0.6007	0.5395	0.5996	0.5434	91.30	89.81	90.63	90.2
C 1820	1000	0.5998	0.5184	0.6003	0.5243	0.6010	0.5278	86.43	87.34	87.82	87.6
A 1618	1000	0.5998	0.5560	0.6005	0.5489	0.5995	0.5674	92.70	91.41	94.65	93.0
B 1618	1000	0.5999	0.5363	0.5996	0.5286	0.5996	0.5205	89.40	88.16	86.81	87.5
C 1618	1000	0.6000	0.5050	0.6005	0.4930	0.5996	0.5049	84.17	82.10	84.21	83.2

After having observed this universal ranking, bigger diamonds were tested still. Including sizes up to 16/18, next logical and still relevant to Hilti AG product portfolio were sizes 14/16 and 12/14. With this information, Hilti AG would have a broad range of data for a broad product range, and a unique opportunity to correlate laboratory properties with real-world usage.

For sizes 12/14 – 18/20, three grades of product from the same manufacturer were tested. For friability testing of this size, sieve sizes 1400, 1180, 1010, 850, 710, 600, 505, 425 were used. In table 8, different sieves that were used with different sizes are shown. Each capsule was filled with 2 carats (1 carat = 0.2 grams), or at least as close to it as possible. Table 9 shows results (3 average values per sample), which were obtained during friability testing.

Table 9: Final results of the friability testing

Type	Size	Capsule	Weight	Res-1400	Res-1180	On-1010	On-850	On-710	Catchpan
A - Premium	1214	AVG	0.4011	0.2135	0.0645	0.0186	0.0187	0.0121	0.0645
B - High-end	1214	AVG	0.4008	0.2976	0.0495	0.0104	0.0087	0.0049	0.0267
C - Mid-range	1214	AVG	0.3983	0.3039	0.0430	0.0088	0.0074	0.0019	0.0286
Type	Size	Capsule	Weight	Re-1180	Re-1010	On-850	On-710	On-600	Catchpan
A - Premium	1416	AVG	0.4009	0.0651	0.0770	0.0679	0.0391	0.0273	0.1161
B - High-end	1416	AVG	0.4004	0.3144	0.0255	0.0154	0.0103	0.0047	0.0276
C - Mid-range	1416	AVG	0.4010	0.3326	0.0236	0.0103	0.0052	0.0050	0.0215
Type	Size	Capsule	Weight	Re-1010	Res-850	On-710	On-600	On-505	Catchpan
A - Premium	1618	AVG	0.4003	0.3475	0.0159	0.0095	0.0061	0.0025	0.0127
B - High-end	1618	AVG	0.3998	0.3313	0.0256	0.0110	0.0080	0.0051	0.0170
C - Mid-range	1618	AVG	0.3991	0.2870	0.0318	0.0218	0.0139	0.0094	0.0322
Type	Size	Capsule	Weight	Res-850	Res-710	On-600	On-505	On-425	Catchpan
A - Premium	1820	AVG	0.4000	0.3402	0.0181	0.0142	0.0064	0.0046	0.0163
B - High-end	1820	AVG	0.3993	0.3233	0.0229	0.0120	0.0073	0.0064	0.0221
C - Mid-range	1820	AVG	0.4000	0.3032	0.0291	0.0145	0.0111	0.0083	0.0280

Remains of diamond grit/dust were carefully removed from corresponding sieves and weighted on a scale. After data collection, PPC and toughness indexes were calculated, with some curious findings.

As shown in table 10, similar expected ranking was observed, until sizes 14/16 and 12/14 were tested, in which case some ranking deviations were observed. In these instances, it appears as higher A grade diamonds are behaving poorly in comparison with lesser grades B and C.

Table 10: Results from friability testing

Product	Test cycles	Toughness index
A 1820	1000	90
B 1820	1000	87
C 1820	1000	83
A 1618	1000	91
B 1618	1000	89
C 1618	1000	80
A 1416	1000	35
B 1416	1000	89
C 1416	1000	80
A 1214	1000	69
B 1214	1000	87
C 1214	1000	87

Product	Test cycles	Toughness index
A 1820	1000	90
B 1820	1000	87
C 1820	1000	83
A 1618	1000	91
B 1618	1000	89
C 1618	1000	80
A 1416	1000	35
B 1416	1000	89
C 1416	1000	80
A 1214	1000	69
B 1214	1000	87
C 1214	1000	87

As shown in figure 41, comparing the residue from sizes 12/14 and 14/16, a clear difference can be seen in a form of finer dust and cleaved particles.

Figure 41: Diamond residue after friatesting, size 12/14, grade A

Data from friability testing is graphically presented in figures 42 and 43.

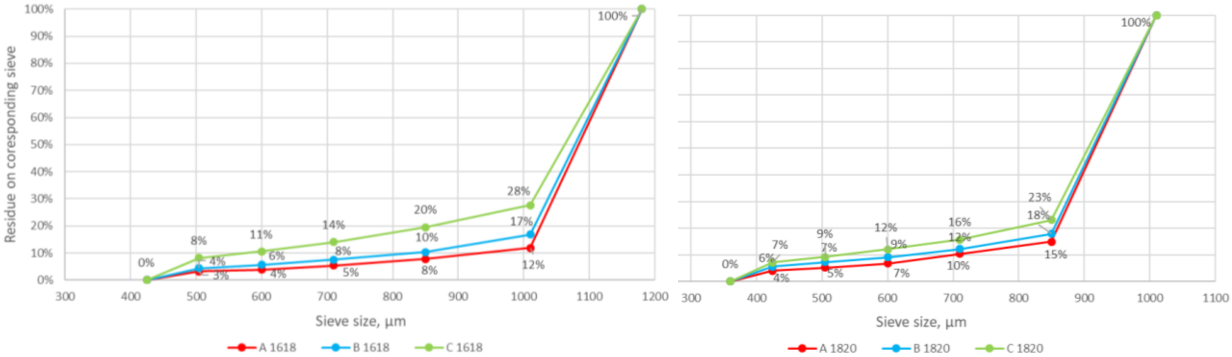


Figure 42: Residues on sieves after friability testing, sizes 16/18 and 18/20

Figure 42 shows the percentage of diamond residue from friability testing on corresponding sieves. Residual diamond particles are in direct relation with friability index, meaning the lesser the amount of particle left on sieves which are finer then corresponding on-size sieve grade, the greater the diamond toughness. This confirms the established diamond ranking system, clearly showing grade A as having lesser amount of residue on sieves below the corresponding sieve grade. But with sizes 12/14 and 14/16, as shown in figure 43, results change dramatically. In this case, diamond grade A shows inferior performance to lesser grades B and C, having a larger amount of finer residue on other corresponding sieves, which can also be seen in figure 43.

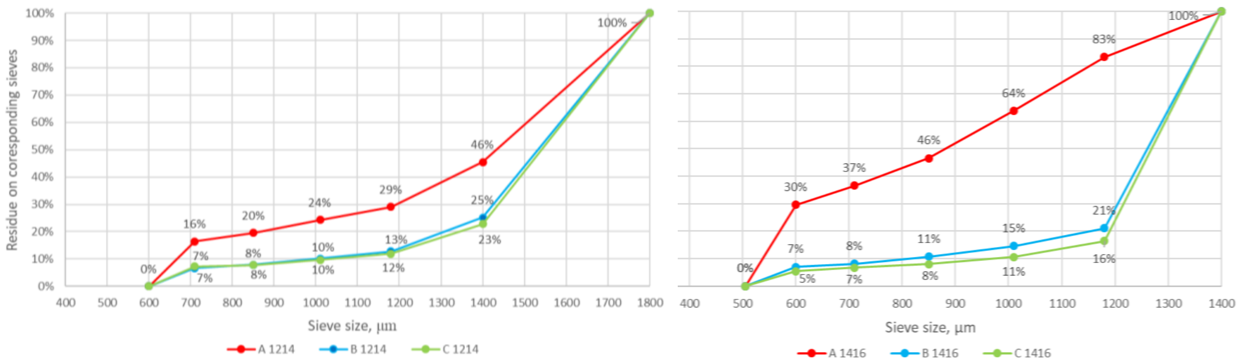


Figure 43: Residues on sieves after friability testing, sizes 12/14 and 14/16

Mechanism behind this is yet unclear, so the next step of testing procedure would be gathering more data with particle image analysis and individual particle testing, using universal compressive strength tester.

6.2. Diamond crushing

Individual particle diamond crushing has been carried out on compressive strength tester, equipped with Zwick/Roell 250 kN force sensor, as shown in figure 44.

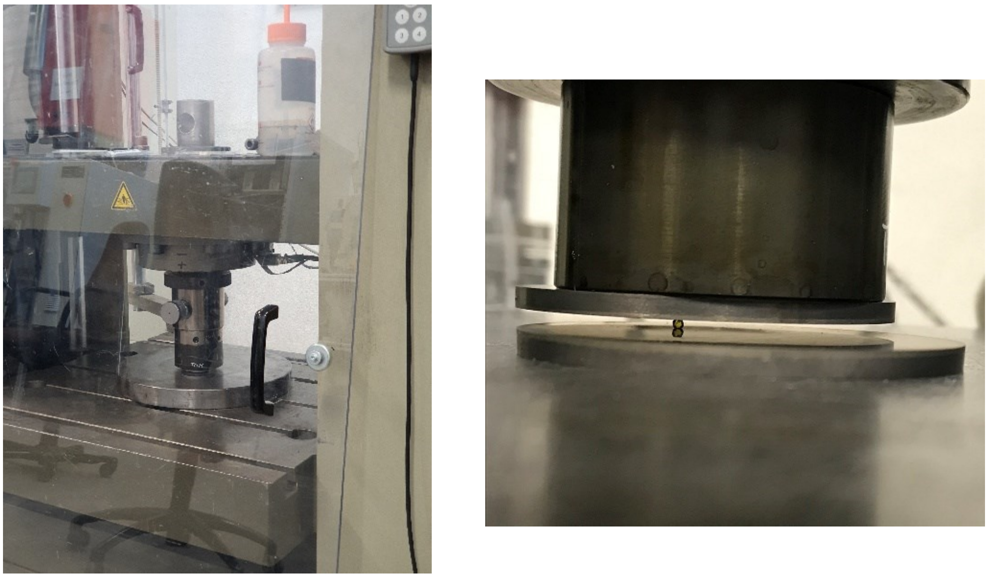


Figure 44: Zwick/Roell force sensor 250kN with single diamond particle sandwiched between PCD plates

Idea behind diamond crushing is to analyse the behaviour of individual particles, in a large enough quantity. Observed mechanical properties could then represent properties of the entire batch. Each particle has a slightly different shape and size, so it is of high importance to test large enough number of particles to account for variances between them. In figure 44 testing setup is shown, diamond particle is placed between PCD plates, and diamond crushing sequence is started.

Testing is carried out using pre-loading force of 20 N, to compensate for any movement of particle, with the testing speed of 0.1 mm/min.

As shown in tables 12 and 13, two grades of diamonds were tested, grade A – Premium, and grade C – mid-range. Mean values ($\bar{x}$) were taken using 12 testing samples, as well as standard deviation (s) and variance (v). There are no significant differences between diamond grades in sizes 12/14 through 18/20.

Table 11: Diamond crushing results, sizes 12/14 & 14/16

A	F_{max}	displacement	A	F_{max}	displacement	A	F_{max}	displacement	A	F_{max}	displacement
1214	N	µm	1416	N	µm	1618	N	µm	1820	N	µm
x̄	5559.436	176.303	x̄	4004.757	156.751	x̄	2773.718	133.983	x̄	1579.727	113.752
s	1587.989	33.939	s	1874.184	29.288	s	1089.044	31.540	s	780.169	43.190
ν	28.564	19.251	ν	46.799	18.685	ν	39.263	23.540	ν	49.386	37.969
C	F_{max}	displacement	C	F_{max}	displacement	C	F_{max}	displacement	C	F_{max}	displacement
1214	N	µm	1416	N	µm	1618	N	µm	1820	N	µm
x̄	5238.553	195.890	x̄	3809.488	171.598	x̄	1463.991	104.744	x̄	1420.935	105.716
s	2014.764	20.822	s	1424.522	29.833	s	1081.956	31.568	s	485.064	27.455
ν	38.460	10.629	ν	37.394	17.386	ν	73.905	30.139	ν	34.137	25.970

After all relevant data was extracted, data from friability testing and compressive strength testing were compared in table 11 and figure 45.

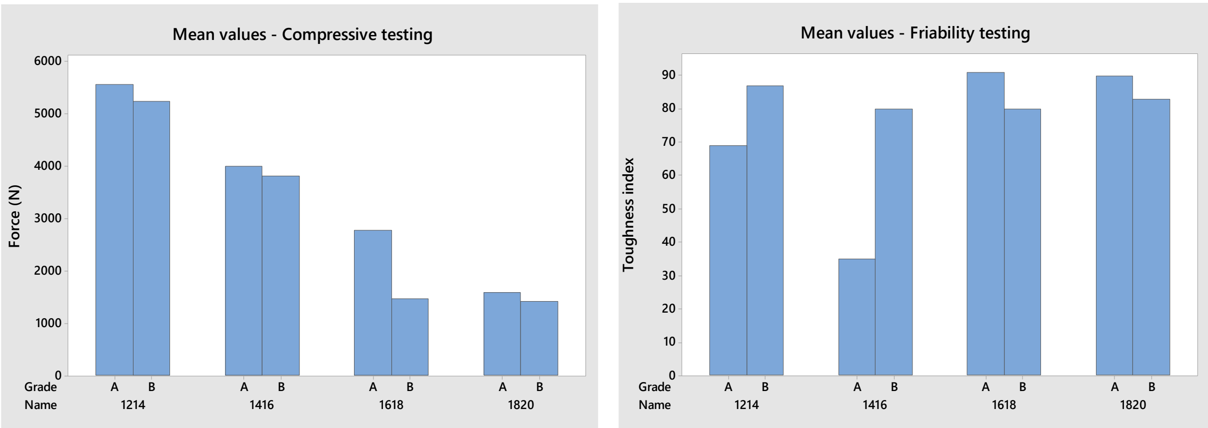


Figure 45: Mean values of compressive strength and toughness index sizes 12/14 to 18/20

As expected, premium grade diamond A has a higher compressive strength value than mid-range diamond C, especially in size of 16/18. With this individual particle test, an expected ranking is observable, which can't be said with friability testing of sizes 12/14 and 14/16, which are quite opposite to crushing results.

Compressive strength results are lower with finer sizes because the particles are simply smaller and offer lesser individual surface area and therefore load bearing capability, whereas the friability test results don't change so much from size to size because they are always tested using sieves specific to the size – friatesting results are slightly size normalised.

6.3. Image Analysis

Image analysis was conducted on sizes 12/14 and 18/20, with diamond grades A and C. These sizes and grades show significant differences in friability testing. Test was conducted with a use of Diainspect-P particle image analysis system. In figure 46, cumulative probability distributions of ellipticity for four samples of interest are shown.

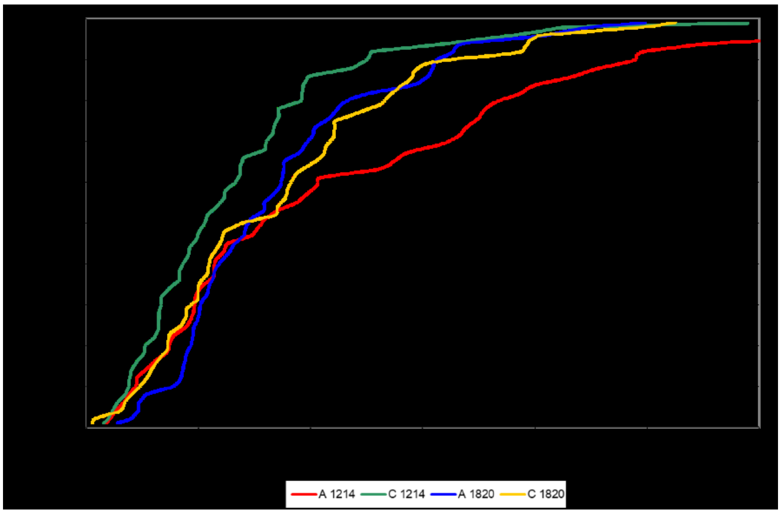


Figure 46: Cumulative probability distribution of ellipticity

Reason behind differences between sizes 12/14 and 18/20 (with premium grade diamonds) was difficult to explain with diamond crushing, but particle analysis sheds some light onto this problem. One of the key factors that relate to diamond strength is ellipticity, the closer the number to 1, the better.

As shown in figure 46, ellipticity of tougher diamonds tends to be closer to 1 over a wider range of cumulative probability, while the outlier, diamond grade A in size 12/14 has a less favourable distribution of ellipticity. This difference could lead to different diamond toughness indexes but is certainly not the exclusive factor.

7. Failure mode analysis – core drilling

In the construction industry, there is a need for tools and accompanying hardware which enable core drilling operations. Hilti AG has a broad portfolio of different core drills, tools and complete systems. In 2015, a new generation of inserts was developed called X-change modules. These modules are not directly welded onto a barrel, rather can be removed quickly when they reach end of life. These modules enable higher flexibility and greatly improve ease of use and reduce tool downtime.

Figure 47: Hilti's coring barrel with x-change module [24]

X-change module is made from few key components, metal-matrix segments with diamonds, which are laser welded to a steel metal crown, enabling easy mounting onto a barrel.

Figure 48: X-change modules, crown and segments [24]

Hilti AG is utilizing a wide variety of segment bonds, diamond specifications (size, distribution, concentration, etc.) to accommodate needs for different coring applications, creating a broad product portfolio. In next pages, core drilling is explained, with crucial information regarding tool handling and usage.

Core drilling is one of the most effective, non-vibratory ways of drilling through reinforced and non-reinforced concrete surface. It creates holes, which could be described as tunnels, without causing aggressive demolition or too much strain on concrete, retaining its structural properties.

The core drill is a highly efficient and powerful tool for boring holes through reinforced concrete, block, brick, masonry, and stone.
The typical core bits are made of hollow steel cylinders that are fitted with segmented diamond teeth. The teeth grind away the concrete surface creating a hole of any desired size.

Usually, core bits vary in size from 10 mm to 350 mm in diameter. Most core bits are capable of drilling through 300 mm of depth and some even more. For special applications longer extensions, threaded barrels are also available in selected product ranges, suitable for special use cases and needs.

Figure 49: Hilti AG diamond coring system in application [24]

Diamond drilling is preferred to alternative forms of drilling (for example, percussive drilling with cemented carbide cutters) when the required holes have large diameters or contain a high amount of reinforcement. The core drilling procedure is most effective in getting precise and accurate circular cuts through various concrete surfaces.

Reinforced and non-reinforced – both types of concrete are often encountered in highway drilling and construction applications. Both require unique drilling methods and differ in drilling results.
For instance, drilling through steel bar produces different stresses and therefore, has a different wear on the cutting surface. Thus, it is important to determine the type of concrete first and then choose the right drilling equipment that will perform the job efficiently.

Figure 50: Reinforced concrete [25]

The significance of core drilling is unparalleled. Unlike traditional drilling procedures, diamond drilling is more comprehensive in nature and environmentally sound. Key benefits of core drilling include:

- Core diamond drilling is most efficient where precise circular cut and continuous holes are required.
- Core drilling method can be equally used for reinforced as well as non-reinforced concrete surfaces.
- Holes of virtually any diameter can be drilled to make openings for electrical, plumbing, and HVAC installation.
- Core drilling can also be used for sampling and analysis of rock and structures.
- Coring produces less vibration and strain, compared to conventional methods, minimizing structural damage.
- With right drilling procedure, accuracy can be increased, while decreasing labour time and cost.

Drilling through reinforced concrete surfaces can be difficult and it takes longer than for other concrete and allied materials.
For this, the core drilling procedure is adopted. This is where the steel bar of reinforced concrete is drilled through by fine diamond crystals in a machining mode. However, it puts a high strain on the diamond core bit as steel is a relatively ductile and very tough material.
When the core bit rotates against the same section of drilling surface, it encounters concrete that's more brittle than before. This facilitates loading and unloading of diamond crystals and bond materials.

Drilling through plain concrete is relatively different from that of reinforced concrete. However, the core drilling method can also be used in cutting holes of any diameter through non-reinforced concrete surfaces.
Here, the concrete material is removed or drilled through the process of crack propagation. Diamond in the core bit generates stress on brittle non-reinforced concrete that creates a crack on the surface.
The cracks are caused when the concrete is broken away from base material, allowing the core bit to drill through the material efficiently.

Some key factors in core drilling are listed and described on the next page, like water usage, relationship of diamond, bond and drilled material, force/pressure, power, speed and torque. These factors need to be taken into consideration when approaching core drilling.

1. Water – If wet drilling is taking place (concrete), it is preferable to use little water. This enables the diamond to grind away the concrete surface efficiently. Excessive water pressure can wash away generated abrasive slurry, preventing the diamonds from becoming exposed. Appropriate slurry helps in the grinding process and keeps the core bit cool. The diamonds remain exposed all through and stay in contact with the slurry particles.

2. Rig based, hand-held drills – For small diameter (up to 152 mm maximum), non-intensive job and low power tools (max 1.7 kW) hand-held drilling can take place. In more demanding conditions, operation is generally conducted rig-based where the drill motor in mounted of a drill stand.

3. Diamond and bond – To get the best results, it is important to choose a diamond type that matches the application. For this, it is imperative to consider the material to be drilled (mentioned in section 5.1.5.) and diamond bond specifications of the core bit. Too soft a bond may wear away the diamond prematurely; too hard a bond may increase drilling time. For reinforced concrete, choose a soft diamond matrix; for softer materials, choose a hard diamond matrix.

4. Applied force/pressure – For efficient drilling through reinforced and non-reinforced concrete surface, maintaining steady and even pressure is most important. Too little pressure than required for the application can cause the diamond to glaze over. On the other hand, too much pressure can overload the drill, causing significant damage to the drill motor and core bit.

5. Power, Speed and Torque – To grind through surfaces efficiently and prevent the glazing of diamond segments, it is important to set the motor at the correct speed (rpm), and right gearing for needed torque output. As a rule of thumb used in the industry, the target is to aim for a peripheral speed of the core bit between 2 and 4 m/s. A smaller diameter core bits require higher rpm and lower torque, and opposite is true with larger diameter core bits. To achieve the right drilling speed, it is imperative to have adequate power. If the drill motor is underpowered, it can cause overheating during drilling, thus, damaging the tool or leading to the glazing of diamond segments. When the equipment receives too much power, it can also cause increased abrasion (lower than expected life of the core bit) and/or destruction of diamond segments.

Drilling tests have taken place using x-change modules as shown in figure 51. These modules have a specific arrangement of eight evenly spaced segments, and laser welded to the metal crown. This section is to describe the findings of the failure mode analysis of this type of diamonds inserts.

Figure 51: X-change module with visible large diamonds

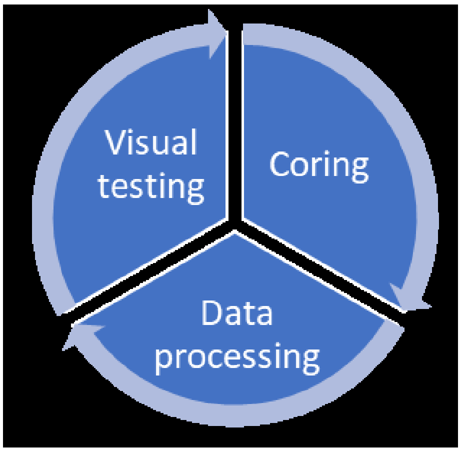
In this instance, specific arrangement of bigger diamonds is utilised, with similar protrusion range. Protrusion refers to height difference between the surface of the bond and highest point of the diamond.

Premises of this project were identifying of levers which could improve performance of selected modules and finding ways of improving and optimising of the design.

All the testing was performed in house, using imaging system designed for close-up analysis. System relies on high resolution cameras with computer and manual control, ensuring high precision in manipulating and pinpointing of single diamond.
Using this system, information regarding diamond protrusion, diamond wear states, could be obtained, on diamond per diamond basis.

Wear state analysis procedure was conducted as followed:

1) Acquiring of initial state of diamond protrusion and diamond wear state.
2) Testing of modules in coring application.
3) Interrupting each test after one hole or half a hole was drilled.
4) After hole was drilled, module was returned to macro imaging system for further analysis.
5) High-resolution images were taken using Canon's EOS DSLR photo camera.
6) Testing procedure was repeated, until module's end of life.



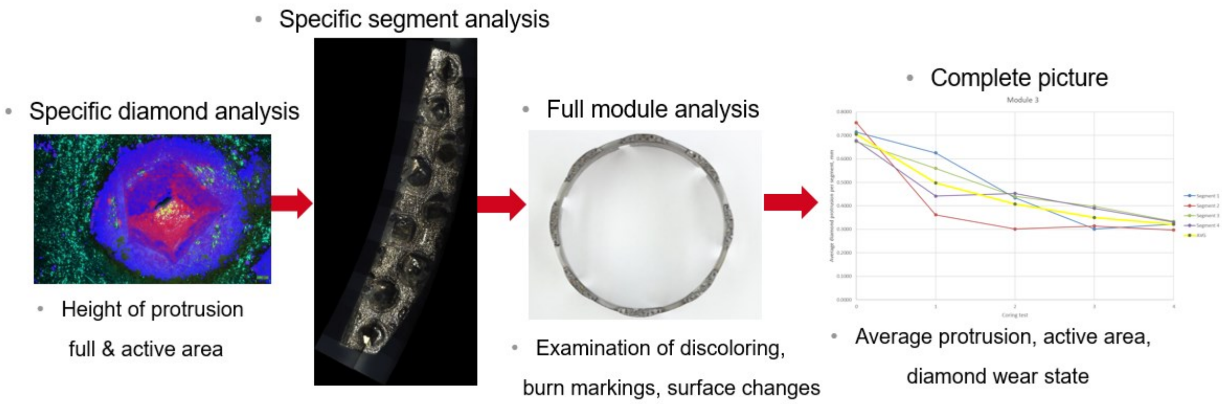


Figure 52: Wear state analysis cycle

In this project, different exchange modules were tested, with different diamond grades, sizes, but using same bond material.

Module #1 – this module uses diamonds which are classified as premium grade, with average diamond protrusion height of 1 mm.
Module #2 – this module uses diamonds which are classified as premium grade, with different segment geometry.
Module #3 – this module is based on classic design as module #1, but instead of premium, it uses mid-range grade diamonds.

Module #4 – this module is based on same design as modules #1 and #3 but is using smaller diamond size.

Module #5 – this module is based on same design as modules #1, #3 and #4, but instead of normal protrusion of 1 mm, diamonds are set to protrude 1.5 mm.

Concrete type A – highly abrasive, low product lifetime, faster cutting speeds.

Concrete type B – less abrasive, high product lifetime, slower cutting speeds.

As shown in table 13, bigger portion of tests were conducted in concrete A, which is more abrasive, and lowers the overall time of testing procedure by more than half.

Table 12: Table of conducted tests

Module number/Concrete Type	A	B
1	✓	✓
2	✓	
3	✓	
4	✓	
5	✓	✓

Initial and consecutive wear states were acquired using macro imaging, in conjunction with high resolution images from Canon camera system or optical microscopes.

Figure 53: Picture taken with EOS mounted camera

Figure 54: Testing setup with DD150 drill, on drill stand

All the tests were performed using DD 150 (DD stands for diamond drill) manual operated tool mounted on a drill stand, with power output of 1.5 kW, designed for use with diamond modules. Optimal speed is indicated by small light piece. When operator feeds the drill too fast, light turns red. When operator feeds the drill too slow, light turns orange. When feed rate is optimal, light turns green. With this system it is easy to stay within optimal drilling parameters.

Before and in between coring sessions, diamonds on surface were analysed with macro imaging system, as shown in figure 55.

Macro imaging system has a feature with which system captures image by image of whole segment, and then stitches those photos into one. This is shown in figure 55, on left-hand side, and it is called mosaic imaging. This imaging method enables quick comparisons between coring testing, and quick appraisal of diamond status.
Alternatively, system enables precise imaging of individual particles (as shown in figure 55 on the right-hand side), for further in-depth analysis. Diamond protrusion can be obtained when focusing on bond surface and afterwards focusing on the top of the diamond. With these two points, system calculates the protrusion of the diamond from the bond.

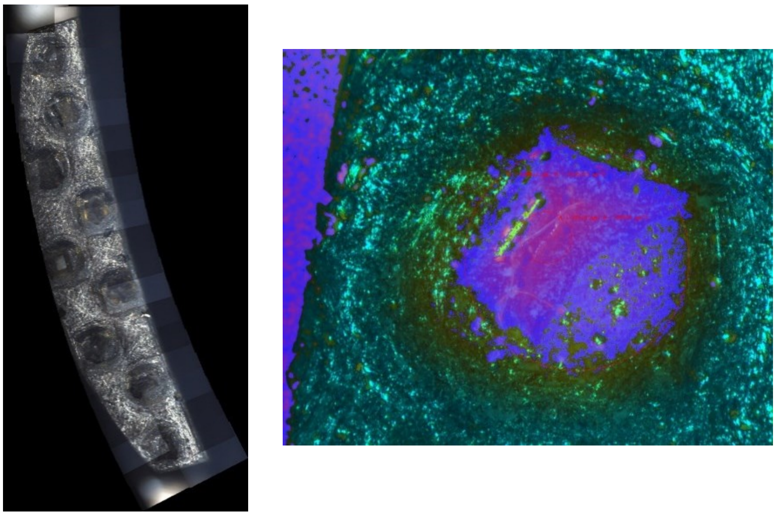


Figure 55: Mosaic and individual diamond picture

This information could in turn shed some light into wear mechanism. After each coring session and data capturing, tables like one shown (table 14) were filled with most relevant information. Table contains information regarding diamond protrusion height, diamond wear state, wear index which correlates with wear state, and diameter of active (working) surface area of the diamond.

Table 13: Example of data output from analysis

Measurment	Diamond height	Wear stage	Wear index	Active diameter, mm	Full diameter, mm
0	0.5732	emerging (auftauchend)	1	0.2510	1.4154
1	0.5691	emerging (auftauchend)	1	0.2758	1.2002
2	0.5937	emerging (auftauchend)	1	0.2857	1.3117
3	0.4938	emerging (auftauchend)	1	0.2877	1.2441
4	0.5100	emerging (auftauchend)	1	0.4683	1.3640

With this information, corresponding charts were created, as shown in figure 56.

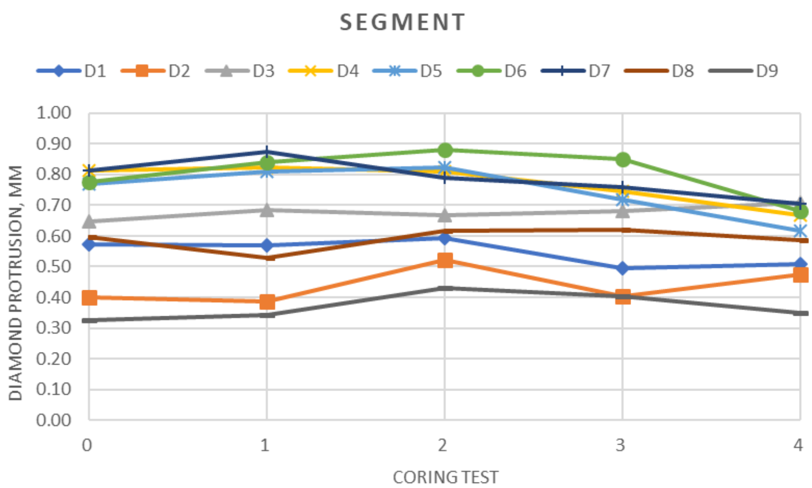
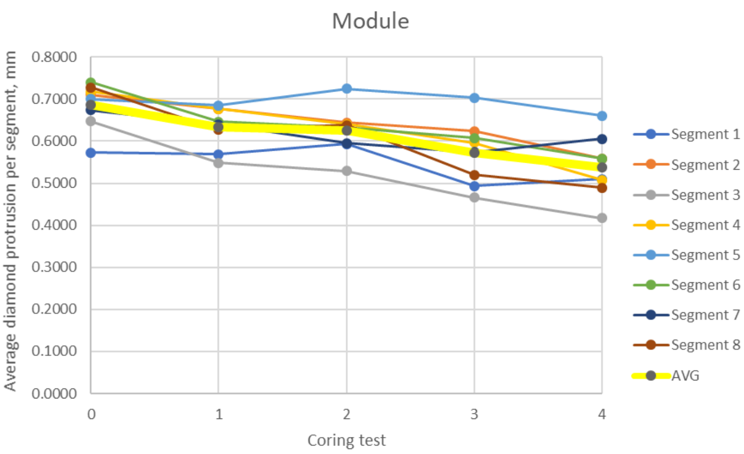


Figure 56: Complete wear state analysis after completed coring tests

Figure 57 shows progression of diamond protrusion and wear state after all the coring tests were conducted. Coring tests were carried out until module stopped drilling. On Y-axis diamond protrusion is plotted in millimetres, and on X-axis number of coring tests is plotted, starting from 0 which corresponds to initial diamond state. 9 exact same diamonds per segment were monitored, and there is a clear declining trend of diamond protrusion, from initial state through coring session number 4.
After each of eight segments was measured, summary chart was created to better understand diamond protrusion evolution of each exchange module.

As shown in figure 57 and table 15, there is a clear decline of diamond protrusion from initial to final test. Average protrusion is marked with thick yellow line.



Coring	0	1	2	3	4
Segment 1	0.5732	0.5691	0.5937	0.4938	0.5100
Segment 2	0.7104	0.6766	0.6446	0.6242	0.5591
Segment 3	0.6476	0.5489	0.5293	0.4657	0.4175
Segment 4	0.7178	0.6763	0.6406	0.5959	0.5078
Segment 5	0.7007	0.6850	0.7246	0.7029	0.6605
Segment 6	0.7399	0.6462	0.6318	0.6080	0.5591
Segment 7	0.6738	0.6401	0.5950	0.5736	0.6053
Segment 8	0.7273	0.6272	0.6384	0.5195	0.4894
AVG	0.6863	0.6337	0.6247	0.5729	0.5386

Figure 57: Average diamond protrusion per module

As shown in figure 58, different combinations of diamond size, quality, protrusion and segment geometry and concrete types yield different results. In general, results presented in this chart could be quite confusing, and require in-depth analysis and explanation.

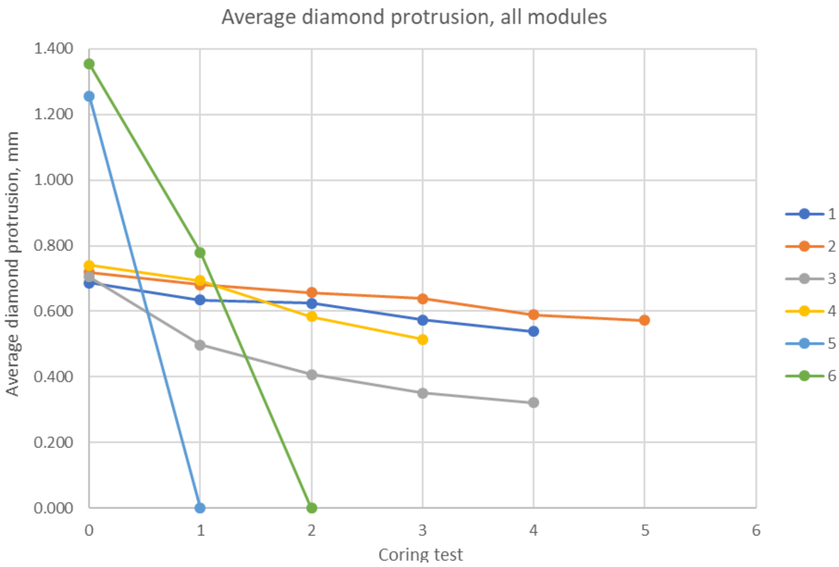


Figure 58: Average diamond protrusion for all tested modules

Modules marked #1, #2 and #4 exhibit similar behaviour. Their protrusion drops from around 0.7 mm to less than 0.6 mm.

Module #3 experiences a bit steeper trend, its protrusion dropping from 0.7 mm to less than 0.4 mm.

And modules #5 and #6 experience catastrophic failure after coring tests one and two.

Longer lasting modules were tested in less abrasive concrete B, and shorter ones in more abrasive concrete A.

Module #1 and #2 are exact same modules, using same bond material, with premium grade diamonds. Modules were tested in different concrete types. Module #1 was tested in more abrasive concrete A, while module #2 was tested in less abrasive concrete B. As shown in figure 58, coring tests shows that module #2 outperforms module #1 in terms of coring lifetime.

These results make sense, coring in less abrasive concrete yields better coring lifetime. That said, both of those modules still have diamond protrusion, which is around 0.6 mm, diamonds are still protruding, but module stops drilling.

After coring tests were finished, all the images before and after coring sessions were analysed. After detailed appraisal of diamonds, same conclusion was reached for these 2 modules.

As shown in figure 59, diamonds still retain their recognisable shape, no catastrophic failure is observed, but instead of sharp cutting edges, they look dulled and rounded.

Figure 59: Close up photo of 2 segments on module #1 and #2

In more abrasive concrete A, we see a more drastic evolution of protrusion, as shown in figure 60.

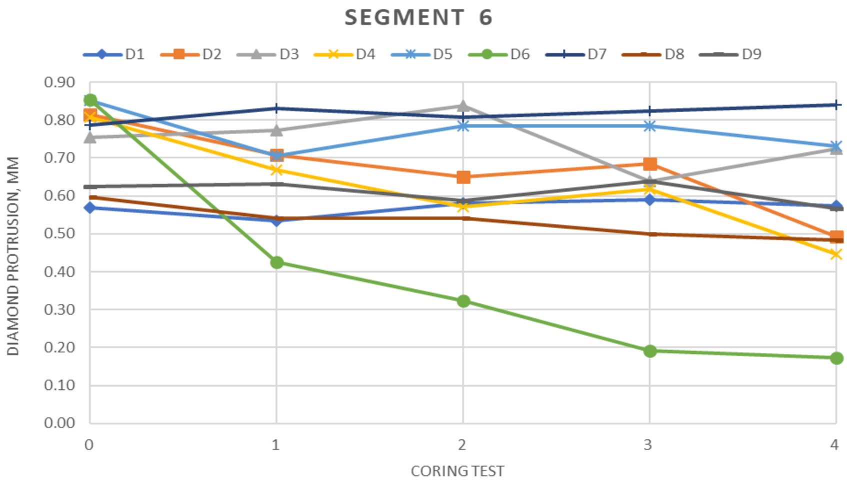


Figure 60: Wear state evolution for segment 6 on module #1

For example, segment 6 of module #1 experiences more catastrophic diamond failure like diamond pull out or faster wear, which contributes to more than double of diamonds being destroyed catastrophically compared to module #2.

Number of coring tests performed were the same, but in more abrasive concrete, module #1 drilled only half a depth per coring test, so in the end, module #2 outlasted module #1 by almost double the drilled depth, which is expected taking concrete abrasivity into consideration.

Unfortunately, no other measures could be achieved to improve this wear performance, using tools from same power class.

Module #3 was similar to modules #1 and #2, but with a different design geometry, which is shown in figure 61. This type of geometry puts more stress on diamonds in the middle, which are positioned higher than ones on the side.

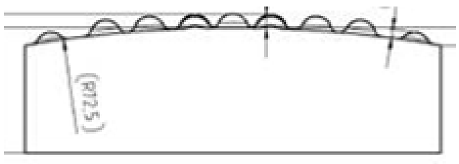


Figure 61: Different design geometry of module #3

Higher stress speeds up the wear rate of diamond that protrudes higher, which in turn stops them from polishing. Results from this test are shown in figure 62.

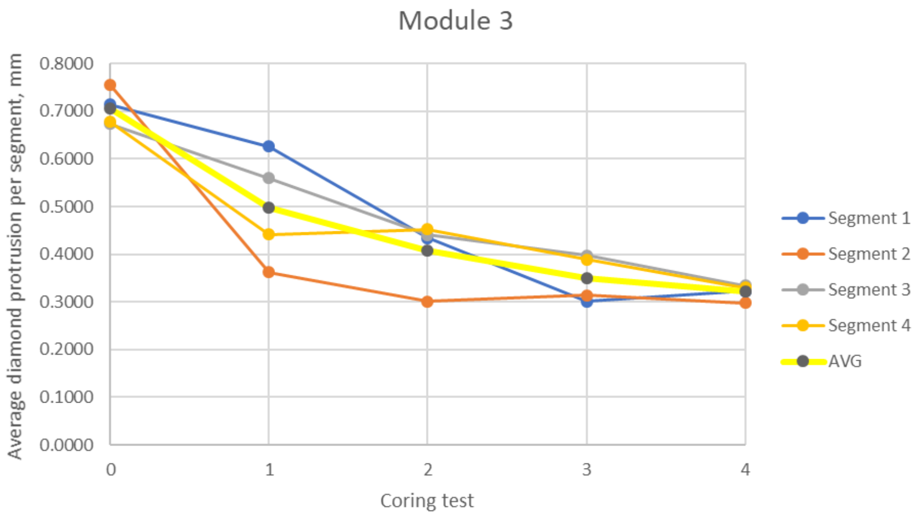


Figure 62: Wear state evolution for module #3

This segment geometry enables faster wear, but also exaggerates catastrophic failure. This module managed to drill only 1.25 holes in abrasive concrete A, which is not suitable in real coring operations.

Module #4 was similar to modules #1 and #2, but instead using mid-range grade diamond. Idea was to jump-start a crushing process of diamonds a bit earlier, thus avoiding loss of sharp cutting edges of the diamond which occurred in modules #1 and #2. Results are shown in figure 63.

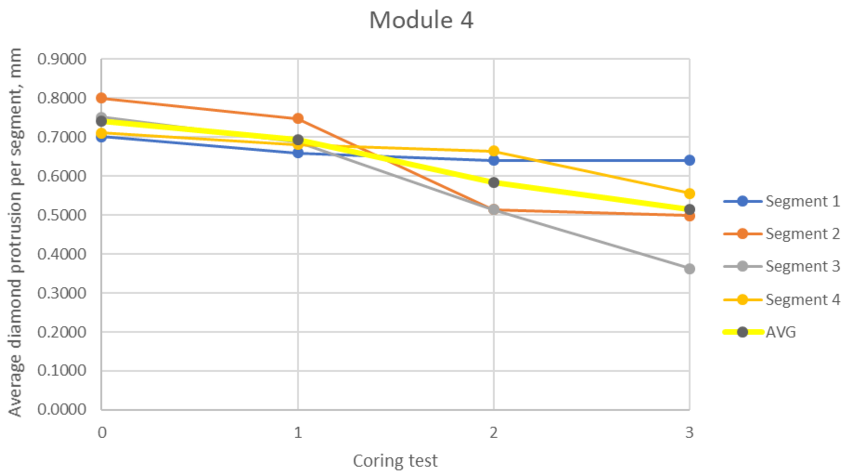


Figure 63: Wear state evolution for module #4

This module was produced using mid-range grade diamond, explained in chapter 6 of this thesis. With lower diamond grade comes lower toughness and strength. If there is an occurrence of diamond rounding, lower diamond grade could mitigate those problems.

But in this case, opposite happened. Even with more friable diamonds, their cutting shape was not maintained through process of crushing. Lowering of diamond grade led to higher number of catastrophic loss of protrusion and active particles generation. Indeed, more than 30% of particles became inactive compare to module #1 and #2.

As shown in figure 64, there is a high degree of crushed diamonds, which in the end results in lower lifetime.

Figure 64: Close up photo of a segment on module #4

Modules #5 and #6 were the same but drilled in different concretes. These modules were high protruding ones, with protrusion of more than double of previous modules. Aim of this test was to initiate a pulling out process of diamonds thanks to a higher initial protrusion and avoid the dulling of the diamond to take place like observed in module #1 and #2. As seen in figure 65, both exchange modules had similar behaviour, regardless of concrete type.

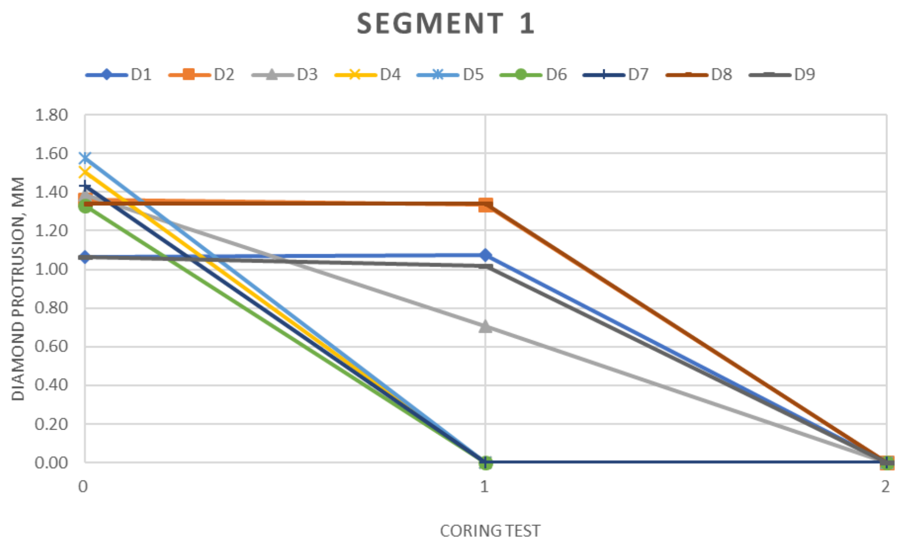


Figure 65: Wear state evolution for segment on modules #5 and #6

Both modules lasted for barely a hole, with extreme pull out of diamonds, as shown in figure 66.

Figure 66: Close up photo of a segment on module #5 and #6

Extremely protruding diamonds are not strongly bonded in bonding matrix. Only a small part of diamond is in the bond, in which case lower forces and stresses are needed to pull diamonds out.

8. CONCLUSION

This paper serves as an introductory piece to diamond as a material, and shows different procedures used for diamond characterisation, as well as application.

In diamond strength testing, diamond crushing didn't show any significant statistical difference in tested samples, due to the very small sample size which was able to be tested in reasonable timeframe.

Friability testing yielded some unexpected results, with diamond grade appearing to be misranked. Large diamond grits were tested with analogous testing procedure as smaller diamond grits, but cheaper mid-range diamonds ranked with higher toughness index (TI ranging from 80 to 90), compared with premium diamonds (TI ranging from 35 to 69).

Image analysis was therefore used to decipher the underlying cause of diamond grade misranking. Shape measurements of diamonds after friability testing suggested a different fracture behaviour between premium and medium grade diamonds, where ellipticity parameter was preferable (closer to 1).

Diamonds shape has a large impact in its resistance to fracturing, which in-turn could explain why some lower quality diamonds ranked higher than premium quality ones.

Coring tests showed a variety of test conditions, and in the end served as a reminder that not all the testing yields positive results. After all the available combinations of modules were tested and analysed, no single design was clearly superior. With different combinations of diamonds, segment shapes, protrusions and concrete types, all modules delivered lifetime lower than hoped for.

Nevertheless, these observations were found to be highly valuable for Hilti's understanding, and were gratefully received by the development team.

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Extras

I. CD-R disc