



Origins and development directions of diamond abrasive tools for processing of stone materials

Paweł Rajczyk¹

ABSTRACT:

The technical level of the stone processing tools corresponds to the level of advanced technology of processing stone pieces of a specific degree of hardness. The analysis of historical building objects, e.g. in Ancient Egypt, informs and allows to put forward a hypothesis about the tools used at that time and the advancement of machining technology from the period from 3000 BC, where the small natural grains of the diamond, called amadeus, were used as an abrasive. The historical periods describing the diamond, as a raw material for the production of machining tools, proved that the degree of development of human civilization and the possibility of technical development of many branches of economic life in the whole world is determined by the determinant of machining tools. The study presents the genesis of the development of machining tools with placing and verifying the hypothesis about the production of diamond segments during the construction of the pyramids in Giza, with the 19th and 20th century development of diamond tools. The hypothesis put forward results from the conducted research studies analyzing the behavior of diamond grain in a metallic-tin bond.

KEYWORDS:

diamond powder; stone materials; stone processing; tool development

1. Introduction

The cutting of basalt and granite in Ancient Egypt, as evidenced by the assessment of traces left on the surface of granite on the walls of sarcophagi, drill holes in granite rocks in Giza, was relatively simple in those days, a relatively simple task, which is confirmed by the traces left after the incision in granite rock. Egyptian sources [1–5] announce that 3,000 years old BC in the State of the Pharaohs used abrasive grains of natural diamond to process hard materials. The mentioned period of the pre-history era, which followed the Stone Age and preceded the Iron Age, was called the Bronze Age and was formed in the third millennium BC, where centers were developed in which the skills of metalworking were mastered. In Egypt and the Middle East, the beginning of the Bronze Age is assumed to be 3400 BC. The end of the Bronze Age falls on the years 1000 to 700 BC. The name of the epoch comes from the then used bronze raw material, i.e. a copper-tin alloy in a ratio of 9:1. Examples of bronze objects are: axes, chisels, hoes, sickles, burrows, ornaments and weapons in the form of spear blades and arrowheads. Over time, lead was used instead of tin in similar proportions. The addition of the structure-modifying metal made the bronze as a composite much harder than copper. However, bronze remained a material so soft that in the case of making weapons, swords or axes, they lost their properties in a very short time. The dependence of work and the abrasive properties of diamond segments, which constitute the basic abrasive element in lance drills for granite, marble, concrete

¹ Częstochowa University of Technology, Faculty of Production Engineering and Materials Technology, al. Armii Krajowej 19, 42–201 Częstochowa, e-mail: rajczyk.pawel@wip.pcz.pl, orcid id: 0000-0001-5363-7337

and grinding discs, indicate that the hardness of the binder is an important property of the diamond segment. This parameter in the last twentieth century was shaped mainly with the use of a copper binder, which brings us to the technical possibilities of the Bronze Age. When constructing segments for diamond tools, the principle was applied that soft copper-based binders for diamond segments are used to process hard materials. It results from a detailed analysis of the work of a single diamond grain embedded in the metallic matrix of the diamond segment binder. The one of properties of diamond abrasive segments mentioned, considering mainly binders, defines their hardness applicable in the practical use of materials applied for processing hard granites. Until now, traces of machining allow to partially confirm the hypothesis about the emergence of diamond segments on metallic binders of historical times of building granite objects in Giza, which took place in the Bronze Age in Ancient Egypt. Specialists in the production of machining tools discovered this property and successfully applied their discovery in practice. Another period in which civilization appreciated the importance of super hard processing tools as an aspect which influenced the development of technology was the end of the nineteenth and twentieth centuries. From the mentioned periods, we have collected a richly documented description of the development of tools made of natural and synthetic diamonds.

2. Timeline of application and development of diamond tools

Natural stone is a material with a large number of varieties characterized by individual physical, mechanical and functional properties, as well as the richness of colors and texture surfaces with varying dynamics of utility models. Expectations are directed to new technological solutions that affect the increase of efficiency, increase of quality, increase of work safety and reduction of machining costs. At present, as it appears from the publication [6–8], there is a lot of interest in the global economy in increase of the production of tools made on the basis of synthetic diamond powders on synthetic binders. The historical use of diamond as an abrasive for processing basalt and granite has already been noticed in Ancient Egypt, as evidenced by the traces of cuts in stone on the buildings in Giza. Egyptian sources inform that 3,000 years old BC the state of the pharaohs used abrasive grains of natural diamond called amodeus, which were embedded and sintered in a copper-tin, tin or lead composition [3, 4]. In our era, the development of abrasive tools, documented by publications, was introduced in the fifteenth century, by the Romans, by whom diamond dust was used for the treatment of jewelry diamonds. Petrie [5] in 1880 expressed, how he was amazed that such effective tools could be during the construction of Giza. In his work [9], the author informs on the basis of archaeological research about the discovery of a village of workers in which there were so-called copper workshops, which indicates the convergence of the indicated thread with the hypothesis about the beginning of using diamond tools with segments on metallic binders.

In order to learn the detailed development path of tools with diamond abrasive segments, a diamond as such, should be defined. This mineral is a polymer modification of the chemical element of carbon in nature, among which we distinguish: soot, anthracite, graphite, coke and diamond. The differences between the modifications occurring consist in the construction of the crystal lattice, it is flat for graphite, while for the diamond it is spatial, tetrahedral as in Figure 1.

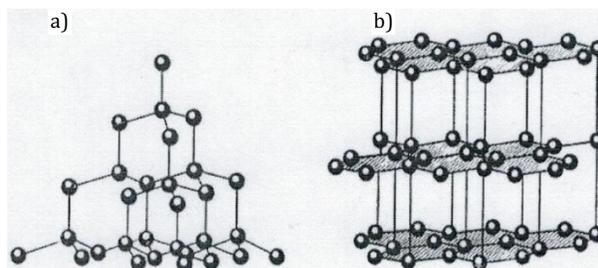


Fig. 1. Crystal lattice: a) diamond; b) graphite [10]

Diamond is the hardest material found in nature – hardness 10 on the Mohs scale, due to this feature it is classified as abrasion resistant material. The diamond is resistant to compressive loads, has high heat conductivity, is resistant to impact loads, has a thermal resistance of 656°C, with low coefficient of friction, the lowest thermal expansion coefficient, it is biologically inert. At 1000°C, the crystal lattice of the diamond transforms into graphite. At present, diamond for technical and tool applications is obtained in an industrial manner in the form of synthetic powders, which are a basic component for the production of working segments of tools that are equipped with circular saws, rope saws, cutting chains, lace drills, grinding discs.

The use of synthetic diamond powders to manufacture segments for machining tools is related to its properties, mainly hardness. Diamond can be scratched only with another diamond. The history of the past century was a period of aspiration for the widespread use of diamond in processing technology, as evidenced by the analysis of literature [11]. Widespread availability due to the very high price until the middle of the 20th century was limited and had been recorded with descriptions of important events related to these tools. The first mention of the diamond is in the description of the work by Pliny the Elder *Historia Naturalis* – glow, hardness, the possibility of using diamonds for engraving". Pliny the Elder (23–79 years BC) author of an encyclopedia in Latin. He indicates the practical use of natural diamonds, where he draws attention to the mineral that can be used to engrave another material. In 1766, Smithson describes that the diamond is a form of crystalline elemental carbon, that's how he began his first experiments with diamond synthesis. In the years 1862–1864, the practical application for the diamond was indicated by the engineer Loshe who carried out the construction task in the Swiss Alps. He developed a method for the technical use of diamonds in drilling processes. In 1910, Albert Shintt in Germany patented his grinding discs with diamond powders applied to their surfaces. In 1920–1930 in Germany there was a lot of interest in the use of diamond tools in mechanical processing. From 1940, continuous research into the production of synthetic diamonds began in Germany, the USA, Sweden, Japan and the USSR. The first synthesis of the diamond was carried out by Baltazar Platen in 1953 in Sweden. In 1955, General Electric conducted the process of diamond synthesis and developed a technology for their production on an industrial scale. In 1965 in Russia, in the laboratory conditions, diamond powder crystals were obtained also in the synthesis process. Synthetic diamonds are known for the technology of their production as HPHT which is decrypted as high pressure and temperature and CVD – chemical vapor deposition process. There is also a new method of synthesis in a pyrotechnic environment since the 1990s. The basis of this method was to create nanoparticles in the process of material explosion with carbon content, the product of this method are nano diamond powder particles. Since 2000, research has been carried out on the method involving graphite processing in high-power ultrasound chambers [12].

Since the beginning of the 21st century, there has been an increase in the availability of synthetic diamonds, where China has a significant share in this development in the production of diamond powders and tools. In diamond technology, it is extremely important to choose a diamond tool for the type of material being processed, which is influenced by factors that can be divided into three groups. The first of these are the properties of the material to be processed and the processing conditions, which should be understood primarily as the hardness and abrasive properties of the material being processed, the processing conditions are: kinematic parameters at which the grain is loaded in the diamond segment binder and the properties of the coolant used. The second group is the properties of the diamond segment, namely the working equipment of the machining tool, among these basic properties there are: hardness, abrasion, concentration of binder modifiers, which is related to the coefficient and degree of heat removal from the diamond segment matrix and the ability to retain the diamond grain embedded in it, which determines the time of its effective use. The third group consists of the properties of diamond powders, among which we distinguish: the type of diamond grain depending on the shape of the grain and its developed surface, on the thickness (graininess) of the diamond grain to which grain strength and abrasive efficiency are related. The performance of the abrasive diamond tool for treating the granite surface is determined by the index of abrasiveness of the

working segment layer, which depends on the properties of the segment binder. The research results show that abrasive wear of diamond grain occurs as a result of: high temperature friction against the material being processed. The output of the segment's work process consist of particles of processed material, particles of the grated segment binder along with fragments of crushed diamond grain particles and coolant forming together the so-called spoil. The key to the evaluation of the phenomenon affecting the maintenance of grain in the segment binder is: hardness of the processed material, kinematic parameters of the drive device, which in total shape a specific surface feature after machining [6, 13, 14]. According to the authors A. Bakoń and A. Barylski diamond grains and micrograins WPG constitute currently a strategic raw material among diamonds. There is a marked fluctuation in terms of its demand and supply depending on the political and economic situation in the world. In the 21st century, industrial demand for diamonds grows particularly in the nuclear and optics technology [8].

3. Study of the properties of an abrasive diamond segment in a tin binder

In order to check the abrasive efficiency of diamond segments produced on metallic bonds identified and highly probably used in Ancient Egypt, diamond segments were produced using synthetic 40/45 # grain diamond powder mixed with powdered tin, which were then placed in a copper cylinder with a diameter of 10 mm and 15 mm high, the segment so made was subjected to an annealing process at 200°C, compacted by pressing. The segment produced in this way, constituting the type of working tool bead, had the embedded diamond grains in its structure, which later enabled the use of such a segment – a bead as an abrasive piece in the construction of drilling, grinding and cutting tools. According to the hypothesis, the main material for making the segments were soft tin binders or tin-lead casing in a copper shell housing, which in the days of Ancient Egypt could be mounted on bamboo stems and which constituted a part of machining tools. The diamond segments themselves could be attached to drilling tools to a suitably prepared dried bamboo stalk, which after their joining was soaked in water to consolidate – annealing with the segment. Forms of segments could resemble geometrical elements as shown in Figure 2.

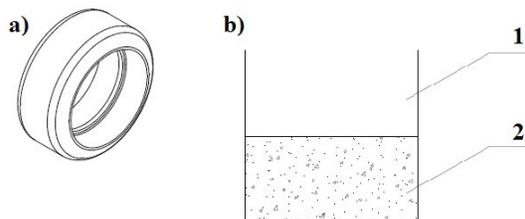


Fig. 2. Sketch of the probable geometrical shape of the diamond segment manufactured in copper workshops acc. author's hypothesis: a) saw equipment; b) drill equipment, where:
1 – copper shell housing, 2 – tin-lead binder with diamond [10]

The assumption of such a hypothesis results from the current knowledge describing the development of contemporary diamond tools and descriptions from the research presented in the literature and from own research in the field of tool material engineering. The results of the research show that binder with low hardness and high abrasiveness is used to treat hard materials, which is part of the technical capabilities of tool workshops at the time of Ancient Egypt. The binder is the so-called matrix in which the diamond abrasive grains are embedded. The segment matrix holds the abrasive grains until it has sharp edges, i.e. when they abrade the processed material. The quality of the binder depends on the degree of utilization of the potential possibilities of hard diamond crystal grain. Data in the literature [6, 8, 14, 15] of the effectiveness of binder usage are confirmed by features such as the appropriate strength of fixing the hard grains of diamond crystals in the binder. Appropriate resistance to wear, the possibility of diamond grain joint impact with binder below the active diamond grain

destruction temperature (656°C). The types of diamond segment matrices depend on the material structure of the segments and especially on the distribution of the diamond powder in the segment. We distinguish the matrices with regular distribution of diamond powder, saturated structure with a high concentration of diamond powder, structure with balanced distribution of diamond powder and structure with low concentration of contained diamond powder. The characteristic properties of the binder in the segment matrix depend on the elements of the material composition, therefore depending on the future use of the properties of such matrices, they are determined at the stage of their recognition before production. The hard matrix is used to process soft materials. The crystal of diamond grain in such a matrix is significantly exposed, as a result of which the diamond crystal grain deeply penetrates the material. There is a small overlap in front of the diamond grain between the workpiece and the matrix, and the process of abrading the workpiece takes place due to the significant amount of diamond grain penetration. The process of binder wear should not take place too quickly, because in this case the diamond crystal grain will be removed from the binder prematurely. The crystal grain will then get broken and destroyed before its effective abrasive properties. Therefore, in the case of processing soft materials, the matrix should be hard so that the grains of diamond powder are kept longer in the matrix of the binder. The soft matrix is desired when processing hard materials, the diamond grain in such a matrix is slightly above the working surface, as a result of which diamond grains penetrate into the work material to a short distance. The clearance between the diamond grain and the workpiece should be very small, due to the low depth of penetration of the abrasive grain into the material being processed and the low abrasive efficiency expressed in the amount of abraded material. Hard material causes quick diamond grain wear and loss of its abrasive properties. Such grains should fall out earlier in order to leave room in the matrix for new sharp diamond crystals, therefore the matrix when processing hard materials should be soft and the size of diamond grains should be small.

The term “diamond powder distribution” is understood as the distribution of individual grains in the segment matrix. The more regular their distribution, the more efficient the abrasive capacity will be, therefore the distribution of diamond powder in the diamond segment matrix is an important criterion for the quality of abrasive efficiency. The distribution of diamond powder grains can only be controlled by destructive testing of the diamond segment. The term “diamond concentration” is understood as the amount of diamond powder per volume of the matrix, the volume base is 1 cm³ of the binder [14]. Only the ideal concentration of diamonds can ensure optimal parameters of abrasive efficiency, taking into account the kinematic parameters of the tool. The concept of ideal concentration is understood as the concentration of diamond powder should adapt to a specific type of material, as previously mentioned, the hardness and concentration of abrasive and binder should be balanced.

The experiment carried out by the author to confirm the hypothesis about the origins of abrasive segments use with an assessment of their abrasive efficiency made in the simplest material variant in a tin binder consisted in placing a tin powder composition mixed with diamond powder grains concentrate 20% in a copper cylinder 15 mm high and 10 mm in diameter and heating the segment sample to 200°C and compacting it by pressing. The segment made this way showed the confirmation of its abrasive properties in dry process against the surface of granite material, which confirms the hypothesis about the origins of abrasive tools used with granite in the above-described sample, which was subjected to a process of abrading with a granite tile surface, where the tin binder was used to carry out the reciprocating motion of 8 cm length carried out in dry conditions, where in the contact with the friction path 10 mb, the spoil quantity of 2.02 g was obtained. After machining the granite surface showed a significant trace in the form of scratches after the abrasion process. Photographs of grains embedded in a tin binder after the abrasion process are shown in Figure 3. Photographs were taken on a Nikon Eclipse MA200 inverted microscope. Analysis of the presented image of grain behavior in the metallic segment subjected to work in the abrasion process, as shown in the publication [10], confirms the trend shown in images of diamond grains preserved in a metallic binder when processing stone materials.

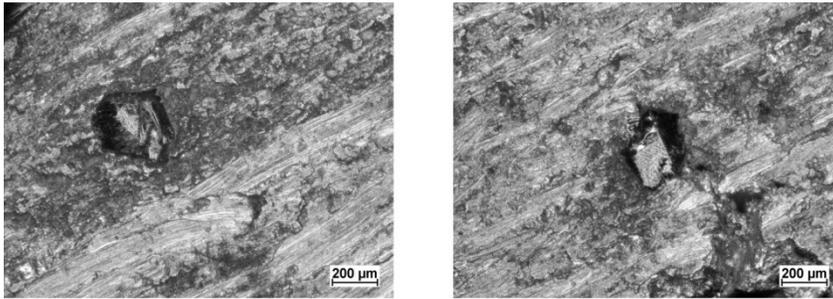


Fig. 3. Microscopic analysis of 40/45 # diamond grains in a tin binder after work of a sample (segment) on the surface of a granite slab, at a magnification of 50x [10]

The experiment carried out showed the convergence of the experimental characteristics of the material of which the segment was made with reference to the hypothesis about the origin of diamond tools dating back to the Bronze Age, which originated in Ancient Egypt.

4. Conclusions

1. The origins of diamond tools used to process granite, difficult to explain, date back to the Bronze Age and Ancient Egypt. This is evidenced by traces of machining on the surfaces of the sarcophagi being processed and drill holes in the granite rocks in Giza.
2. The Bronze Age created the possibilities of building material compositions that were diamond segments on metallic binders, i.e. copper–tin, copper–lead, tin and lead compositions.
3. The development of machining tools always accompanies human civilization, the achievements of the last decade in the development of hard materials exceeding the hardness of diamonds indicate the prospect of a rapid development of technology in the coming century.
4. Currently, an important material in the technology of building diamond tools will be a new chemical composition, in the form of epoxy and polyester resin materials, especially for manufacturing tools for finishing operations in the treatment of stone materials.

References

- [1] Petrie W.M.F., 1833 The Piramids and Temples of Gizeh, London 1990.
- [2] Chrzanowski W., Zalewski F., Jak robili to nasi poprzednicy, Rynek Kamieniarski 2008, 5, 46–52.
- [3] Lipiński J., Koziński W., Cywilizacja miedzi i kamienia technika starożytnego Egiptu, WN PWN, Warszawa 1997.
- [4] Tajduś A., Mikoś T., Chmura J., Pawlikowski M., Kamieniołomy z czasów faraonów w Kairze w aspekcie adaptacji i zabezpieczenia podziemnych obiektów zabytkowych, Górnictwo Inżynieria 2007, 1, 85–94.
- [5] Petrie W.M.F., The Building of Pyramid Ancient Egypt, Part 2, 1930.
- [6] Rajczyk P., Analiza nowych konstrukcji segmentowych tarcz ściernych przeznaczonych do szlifowania granitu, Metody i narzędzia w inżynierii produkcji, Wydawnictwo Instytutu Informatyki i Zarządzania Produkcją, Wydział Mechaniczny, Uniwersytet Zielonogórski, oddano do publikacji.
- [7] Jaworska L., Diament, otrzymywanie i zastosowanie w obróbce skrawaniem, WN PWN, Warszawa 2017.
- [8] Bakoń A., Barylski A., Ziarna i mikroziarna diamentowe – rodzaje ścierniwi i przykłady zastosowania, Wydawnictwo Politechniki Gdańskiej, Gdańsk 2017.
- [9] Dunn Ch., The Giza Power Plant Technologies of Ancient Egypt, 2000.
- [10] Rajczyk P., Ewolucja rozwoju narzędzi diamentowych zapoczątkowana w starożytnym Egipcie, Wydawnictwo Mateusz Weiland Network Solutions 2018, 275–287.
- [11] Woźniak K., Materiały ściernie – wytwarzanie i właściwości, Wydawnictwa Naukowo–Techniczne, Warszawa 1998.
- [12] Konovalov V.O., Petasyuk O.U., Chatechin V.V., Vyznachennya Mitsnosti Zakriplennya Almaznoho Zerna U Zayaztsi Pry Tsyklichnomu Navantazheni, Tekhnichni nauky, Visnyk ZHDTU № 3 (38), Ukraina 2006.
- [13] Rajczyk J., Modelling the geometric structure of concrete work item processing, Applied Mechanics and Materials 2013.

- [14] Knapieński M., Rajczyk P., Innowacyjne metody modelowania diamentowych narzędzi obróbczych do szlifowania powierzchni kamienia okładzinowego, Tom 1, Oficyna Wydawnicza Polskiego Towarzystwa Zarządzania Produkcją (PTZP), 564–574, 2018. Youssef M.A., Analytical prediction of the linear and nonlinear behaviour of steel beams rehabilitated using FRP sheets, *Engineering Structures* 2006, 28, 903–911.
- [15] Nadolny K., Nowa generacja ziaren ściernych z ALON zwiększająca efektywność szlifowania, *Mechanik* 2012, 8–9, 670.

Geneza i kierunki rozwoju diamentowych narzędzi ściernych do obróbki materiałów kamiennych

STRESZCZENIE:

Poziom techniczny narzędzi do obróbki kamienia odpowiada poziomowi zaawansowanej technologii prżenia kawałków kamienia o określonym stopniu twardości. Analiza historycznych obiektów budowlanych, np. w Egipcie, pozwala wysunąć hipotezę na temat narzędzi stosowanych w tym czasie oraz dodatkowo na temat zaawansowania technologii obróbki z okresu od 3000 r. p.n.e., gdzie małe naturalne ziarna diamentu, zwanego amadeus, zostały użyte jako materiał ścierny. W pracy przedstawiono genezę rozwoju narzędzi do obróbki skrawaniem wraz z postawieniem i weryfikacją hipotezy o produkcji segmentów diamentowych podczas budowy piramid w Gizie. Hipoteza ta wynika z przeprowadzonych badań, analizujących zachowanie się ziarna diamentu w wiązaniu metal–cyna.

SŁOWA KLUCZOWE:

proszek diamentowy; materiały kamienne; obróbka kamienia; rozwój narzędzi