Study on the diamond’s role in manufacturing engineering and in energy

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Abstract. Due to its outstanding properties, diamond is considered as an advanced material that generates innovation in various applications belonging to many fields. A very short literature overview is proposed about its role in manufacturing engineering and in energy with a focus on some recent discoveries.

1. Introduction

Diamond considered here refers to the well-known allotrope form of carbon having an ideal face centred cubic structure with each carbon atom covalently bonded to its four nearest neighbours in a regular tetrahedron. This perfect structural arrangement coinciding with the sp³ hybrid orbitals of carbon yields a rigid framework, which combined with the strength of the C-C bond gives rise to many outstanding volume and surface properties that would be difficult to detail in this paper. These properties, in their state of knowledge, will be exploited at all times with sagacity and a brief overview of their impacts is proposed here in the context of manufacturing engineering on the one hand and that of energy on the other hand. The referenced [1-5] books have provided the basis for writing this paper.

2. Diamond in manufacturing engineering

The role of materials is paramount for long term success of manufacturing engineering. That of diamond as selected engineering materials is particular. Diamond can perform one, two or three roles: the raw material, the transformed material and that transforming materials. Its roles began very early and are still relevant despite the changes made in manufacturing engineering over time. This means that diamond, as advanced materials do, has always been adapted to industrial realities that have sometimes been real revolutions. The following subsections show how and why diamond caused the implementation of manufacturing engineering.

2.1. The early history of natural diamond

This subsection gives a very short overview of inventions concerning diamond tools and machines until the beginning of 20th c. During this period, two important discoveries were found: the chemical nature of diamond (end of 18th c.) and the crystallographic structure of diamond (early 20th c.) [6].

The first use of diamond as abrasive powder to polish stone axes would date from 2500 BC and as splinters for cutting and drilling tools from 4th c. BC. Progress comes from inventions of tools and machines that facilitated the work of labour with as examples: diamond wheel for shaping and polishing jewels (end of 15th c.), diamond splinters for glass engraving and diamond pantograph (16th
for generating precision patterns and precision surfaces, diamond-studded drill bit (at least from the 18th) for boring into rocks, diamond drawing die (16th c. - middle of 20th c.) for silver and golden wires first and then for tungsten wires filament lamp used in electricity, diamond saw for cutting gemstones (early 20th c.). Uses of diamond in semi-automated machines also appeared at the beginning of 20th c. [7]. Many of these tools and machines already showed, at the time, a very high degree of technology.

2.2. The advent of man-made diamond
In the first half of 20th c., there were real industrial needs and on full of ideas on the potential uses of diamond. Except for the gem-stone industry, natural diamond sourcing was unsuitable or insufficient. It was decided to produce synthetic diamond, thus soliciting manufacturing engineering for a new challenge. Three main industrial processes, still current, emerged in the last of 20th c.: high pressure and high temperature (HPHT), chemical vapour deposition (CVD), and explosive shock. This caused a disruptive innovation in the diamond industry [8] and beyond, introducing new ways of thinking in manufacturing engineering and breakthrough innovations. The research and development into the synthesis and growth of diamond were the basis for new technologies that have allowed either to successfully replace natural diamond or other materials by synthetic diamond, or to functionalize other materials by synthetic diamond coating. A review on the manufacture of gem-quality diamond appeared in 2000 [9] and a chart on the characteristics of HPHT grown synthetic diamond in 2004 [10] marked the beginning of as a second disruptive innovation in gem-stone branch of diamond industry. Referring to 2.1, synthetic diamond, as diamond tool material, has been able on the one hand to significantly improve the performance and life of existing tools and, on the other hand, to tackle more and more difficult and sophisticated manufacturing tasks with new diamond tools suitable for machining an expanding range of traditional or high technology materials. Evidence can be found in the literature about the efficiency of synthetic diamond tools and the quality of processed products [11-16]. Of course, other performances of synthetic diamond could also be mentioned, but whatever the application, these performances are the result of a material that can be tailored to the manufacturing requirements.

2.3. The present and the future of diamond
Today, diamond, testifying the successes of manufacturing engineering, is in a myriad of products commercially available. If many of these products immediately agree, others need to be modified to meet application requirements. This is the subject of intense research both in terms of the characteristics of the diamond and those of the processed products. Furthermore, with the implementation of the current Industry 4.0, diamond is increasingly required as solution to sustainable manufacturing processes, with controlled productivity, material saving and environmental impact reducing. To come back to the field of diamond tools, further developments are ongoing at different manufacturing readiness level. This involves solutions for increasing the tool lifetime, as well as the guaranteed quality of transformed product with new tools [17-18], for controlling in operando the tool wear [19], for sustainable manufacturing alternative [20]. Diamond tool is increasingly integrated in hybrid machines [21]. The next section will provide an opportunity to illustrate the role of diamond in manufacturing engineering related to the energy field.
3.1. Thermal management
Since a long time, due to its extremely high thermal properties already applied in the machining field, diamond is used as heat spreader (also called heat sink) for electronic and optoelectronic devices, to improve performance and miniaturization. Commercially available for a long time, they exist in a wide range which increases regularly with the arrival of new diamond products [22-23].

3.2. Actions in harsh environments of oil and gas industry
Diamond always brings its mechanical performance and reliability in more and more difficult drilling challenges [24] and brings the same qualities in robotic system when it is decided to dismantle the platforms especially in offshore [25]. It also intervenes as boron doped diamond (BDD) electrode when it comes to caustic wastes treatment in the crude oil refining process ongoing [26-27]

3.3. Actions in harsh environments of nuclear industry
Diamond is involved in the construction, maintenance and dismantling of nuclear power plants using nuclear fission. Some machines are able of remotely cutting with design and engineering focused on the safety of the operator and automation [28]. They present sufficient flexibility to be utilised in both maintenance and decommissioning of structures with low to medium levels of radioactive contamination [29]. Diamond is also involved as radiation detector with the possibilities to use it for everyday control of a nuclear power plant or to prevent emergency accident [30] and a diamond-based radiation detector system has been recently developed to measure high dose rates of radiation [31]. For removing nuclear process effluents, diamond intervenes as BDD in apparatuses [32]. For valorising nuclear waste, new technologies are developing to make nuclear-powered battery. These are beta-voltaic cells that use $^{63}\text{Ni}$ or $^{14}\text{C}$ as radiation sources and diamond as Schottky diode for generating electricity. For $^{63}\text{Ni}$ case, a prototype was already built [33]. For $^{14}\text{C}$ case that should lead to a device called ‘diamond battery’, the technology readiness level is currently at a stage between basic technology research and research to prove feasibility.

Nuclear fusion has been considered to be one of the promising methods of future energy resources, generating no carbon dioxide and nuclear wastes at least from the reaction process. Diamond is an indispensable material in fusion technology, acting as window and detector [34-35] in controlled thermo-nuclear fusion of ITER project and furthermore as ablator material [36] in inertial confinement fusion (ICF).

3.4. Actions for waste treatment
Some actions with diamond used as BDD electrode have already been mentioned in the previous subsections. BDD electrodes extend to a multitude of cases. According to [37], they are by far the most employed electrodes and according to [38] BDD is considered as an optimal electrode material for electrochemical oxidation of organic contaminants in the aquatic environment. Commercially available BDD, electrodes offer a considerable choice and can be the object of comparison for a given waste treatment [39]. As it will see later (next subsection), the use of diamond as BDD electrode is not limited to waste treatment and by the way, BDD electrode has been recognized as ‘designer electrode material for the twenty-first century’ [40].

3.5. Actions for energy storage and electricity production
Some actions have already been mentioned in 3.3 with diamond as Schottky diodes. They can be completed by works on betavoltaic batteries [41-43] and alphavoltaic batteries [44]. It can also be added the studies on the roles played by diamond, as BDD electrode, for supercapacitors [45] that can have ultrahigh-power performance and for fuel cells [46] where undoped or doped diamond are also be used as catalyst.
3.6. Actions for solar energy
Diamond, with a special surface treatment that makes it ‘black diamond’, can be tailored to optically and electrically interact with radiation in a solar converter [47], making possible in near future the feasibility and the manufacturing of high temperature solar cells for harsh environments [48]. It is also concerned with thermoionic energy conversion for concentrating solar power (CSP) [49] and recently, a prototype demonstration of a thermoionic-thermoelectric generator for CSP has been published [50].

3.7. Other important actions directly related to energy
Diamond is seen as an ‘ultimate’ semiconductor and it is expected to be employed in next-generation power electronic devices. To solve great challenges in many fields such as automotive, railway and smart grid with the arrival of renewable energies (e.g. photovoltaic and wind energies) [51-52]. Recent advances have been made [53]. Intensive research continues for maximizing device performance up to the limit of monocrystalline diamond properties [54-57].

4. Conclusion
Although described in a little bit superficial and incomplete way, it is shown here that diamond occupies a very special place with paramount roles in manufacturing engineering and in energy. In each of its roles, diamond has, of course, competitors such as other ultra-hard materials or extremely wide-band gap semiconductor materials, but, until now, it is difficult to find another material than diamond that fulfils so many different functions with such success particularly in harsh environments. In fact, the outstanding properties of the material itself enable the development of methodologies and technologies that exploit more than just the required characteristics for a given application. The aforementioned project about the valorisation of the nuclear $^{14}$C wastes as batteries is an illustration. It is not only a way to treat nuclear waste but also a way to produce energy. Diamond, with its long technical history, continues to be one of the most innovative materials. In the given references, it can be seen that the simple basic atomic structure of diamond is able to host extremely useful defects opening the way to new properties. This can lead to new applications through the development of defects science and engineering. Today, R&D, especially in materials science and engineering and in surfaces science and engineering, continues to show that the full potential of diamond has not yet been fully exploited and will still be a source of beautiful surprises in the future.

5. References
[1] Field J E 1992 The Properties of Natural and Synthetic Diamond (London: Academic Press)
[2] Epstein E J 1982 The Diamond Invention (London: Hutchinson)
[3] Spear K E and Dismukes J P 1994 Synthetic Diamond: Emerging CVD Science and Technology (NY: The Electrochemical Society Series, John Wiley, Interscience)
[4] Asmussen J and Reinhard D 2002 Diamond Films Handbook (Boca Raton: CRC Press)
[5] Hazen R M 1999 The Diamond Makers (Cambridge: Cambridge university press)
[6] Bragg W H and Bragg W L 1913 Proc. R. Soc London Ser. A 89 277- 91
[7] Davies M A, Evans C J, Patterson S R, Vohra R and Bergner B C 2003 Proc. of Lithographic and Micromachining Techniques for Optical Component Fabrication II vol 5183 94-108
[8] Rarick C A 2017 Inn.and Sust. 12 91-96
[9] Choudhary D and Bellare J. 2000 Manufacture of gem quality diamonds: a review Ceram. Int. 26 73–85
[10] Shigley J E, Breeding C M and Shen A H T 2004 Gems Gemol. 40 303-13
[11] Tillmann W 2000 Int. J. Refract. Met. Hard Mater. 18 301-6
[12] Uhlmann E, Richarz F, Sammler S, Heitmüller F and Bilz M 2014 Procedia CIRP 24 19-24
[13] Nicholls C J, Boswell B, Davies I J and Islam M N 2017 Int. J. Adv. Manuf. Technol 90 2429-41
[14] Zhang X Q, Woon K S and Rahman M 2014 11 201-11
[15] Goel S, Luo X, Agrawal A and Reuben R L 2015 *Int. J. Mach. Tool Manuf.* **88** 131-64
[16] Bobzin K 2017 High performance for cutting tools *CIRP J. Manuf. Sci. Technol.* **18** 1-9
[17] Wang C C, Wang X C and Sun F H 2018 *Trans. Nonferrous Met. Soc. China* **28** 1602-10
[18] Kawasegi N, Ozaki, Morita N, Nishimura K and Yamaguchi M 2017 *Precis. Eng.* **47** 311-20
[19] Mueller S, Prieske M, Tyralla D and Vollertsen F 2019 *Thin Solid Films* **669** 450-4
[20] Kumar A and Melkote S N 2018 *Procedia Manuf.* **21** 549-66
[21] Oliaei S N B, Karpat Y, Davim J P and Perveen A 2018 Micro tool design and fabrication: a review *J. Manuf. Sci. Eng.* **36** 496-519
[22] Ye W, Wei Q, Zhang L, Li H, Luo J, Ma L, Deng Z, Lin C T and Zhou K 2018 *Mater. Des.* **156** 32-41
[23] Molina-Jordá J M 2018 *Compos. Part A Appl. S.* **105** 265-273
[24] Wheeler D W 2018 *A Lubricants* **6** 841-27
[25] Baranova M A, Boyko A V, Chebyshev S B, Cherkashin I I, Kireev V P and Petrov V I 2016 *J. Phys. Conf. Ser.* **675** 042003
[26] Schreck S, Aiello G, Dieterle S, Gagliardi M, Meier A, Sabin S and Scherer T and Strauss D 2018 ITER ECRH *Fusion Eng. Des.* **136** A 472–6
[27] Kato H, Yamada H, Ohmagari S, Chayahara A, Mokuno Y, Fukuyama Y, Fujiwara N,Miyanishi K, Hironaka Y and Shigemori K 2018 Synthesis and characterization of diamondcapsules for direct-drive inertial confinement fusion *Diam. Relat. Mater.* **86** 15–19
[28] Dong L, Wang Y H and Zang J B 2017 *J. Inorg. Mater.* **32** 673-80
[47] Bellucci A, Calvani P, Girolami M, Orlando S, Polini R and Trucchi D M 2016 *Appl. Surf. Sci.* **380** 8–11
[48] Orsini A, Belluci A, Girolami M, Mastellone M, Orlando S, Prestopino G, Valentini V, Salvadori S and Trucchi D M 2019 *Diam. Relat. Mater.* **93** 1-7
[49] Xiao G, Zheng G, Qiu M, Li Q, Li D and Ni M. 2017 *Appl Energy* **208** 1318-42
[50] Trucchi D M, Bellucci A, Girolami M and Calvani P, *Adv. Energy Mater.* **8** 1802310
[51] Planson D, Brosselard P, Isoird K, Lazar M, Phung L V, Raynaud C and Tournier D 2014 Wide bandgap semiconductors for ultra-high voltage devices. Design and characterization aspects *Proc. On Int. Semicond. Conf*. CAS 35-40
[52] Wellmann P 2017 *Z. Anorg. Allg. Chem.* **643** 1312-22
[53] Umezawa H 2018 Mat. Sci. Semicon. Proc. **78** 147-56
[54] Lee K H *et al.* 2016 *Diamond Relat. Mater.* **66** 67-76
[55] Tallaire A, Brinza O, Mille V, William L and Achard J 2017 *Adv. Mater.* **29** 1604823
[56] Li F, Zhang J, Wang X, Zhang M and Wang H. 2017 *Crystals* **7** 114
[57] Lloret F, Araujo D, Eon D and Bustarret E 2018 *Cryst. Growth Des.* **18** 7628–32