Transactions on Engineering Sciences vol 25, © 1999 WIT Press, www.witpress.com, ISSN 1743-3533

Applications of CVD diamond and DLC coatings

E. Braca, L. Valentini, J.M. Kenny
Materials Engineering Center, University of Perugia,
Loc. Pentima Bassa 21, 05100 Terni, Italy
EMail: kenny@unipg.it

Abstract

The very high interest in diamond and Diamond-Like-Carbon (DLC) has been further increased by the much more recent discovery that it is possible to produce polycrystalline diamond films and coatings by a wide variety of CVD techniques using, as raw materials, nothing more exotic than a hydrocarbon gas (typically methane) in an excess of hydrogen. CVD diamond can show mechanical and tribological properties comparable to those of natural diamond. This review concerns the applications of CVD diamond as related to mechanical properties, and the possibility of an economically viable alternative in many fields to natural diamond and to the traditional HPHT diamond synthesised at high pressures and temperatures.

1 Introduction

The Chemical Vapour Deposition (CVD) technology allows the production of thin films on a thermally activated substrate by gas phase at sub-atmospheric pressures[1]. The discovery of the possibility of diamond artificial synthesis by CVD encouraged a rapid growth in the use of diamond in a wide variety of applications. CVD carbon based films are produced using mixtures of methane and hydrogen (see fig.1) and can range from soft hydrocarbon polymers to Diamond-Like-Carbon (DLC) and pure diamond, following the bonding character of the carbon atoms and the amount of hydrogen in the coating. CVD diamond differs from that produced by high pressure in that it is polycrystalline

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rather than coarse granular. The film deposition does not require large pressures, and because it occurs from the gas phase, diamond can be made to conform to shapes and surfaces of arbitrary dimension, curvature and thickness.

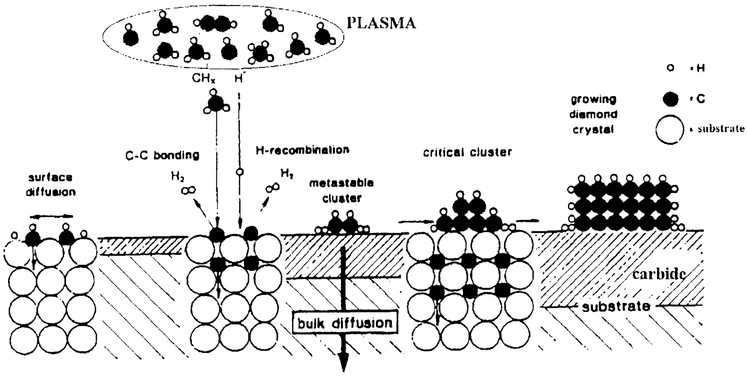


Figure 1: Schematic diagram of mechanism of CVD of diamond[2].

CVD diamond products have reached the market only in last years, and in the future this technology is greatly expected to allow a reduction in diamond production costs for many technological applications. CVD diamond-based products already commercially in use are x-ray windows in electron microscopes, strong abrasion-resistant industrial tools and diaphragms for tweeters in stereo speakers, but they represent only a tin part of applications envisaged.

Particularly, the use of CVD diamond and DLC in mechanical applications is in its early stages. The features of diamond that make it unique and suitable to these applications are: 1] its efficient tetrahedral structure which is stabilised by resonance of the bonding electron among adjacent bonds[3]; 2] the exceptionally high ratios of shear to bulk moduli; 3] the large gap between the top of its valence band and the bottom of its conduction band which make dislocation mobility very low in it; 4] its high surface energy; 5] diamond has the highest known thermal conductivity.

Strength in the context of this review means stability regarding any arbitrary mechanical disturbance. Therefore, a strong material must be able to withstand various modes of strain including tension, compression, torsion, and bending. The theme of the discussion is that diamond and DLC, of all known materials, are uniquely capable in this regard. The reason being that the ratio of its shear stiffness to its bulk stiffness is exceptionally high, and this ratio is a measure of "solidity". Structural materials can become unstable in a variety of ways. They can buckle elastically, flow plastically, twin or fracture. Therefore, no single property determines their stability (strength). The most important properties are: micro geometry, bulk and shear stiffness, dislocation mobility and surface energy. At the molecular level also symmetry is important and for general strength it needs to be as nearly cubic or isotropic. Fibres and membranes can be strong for special kinds of loading, but generally speaking they are not strong as they are penalised by the particular geometry. For these systems elastic stiffness is needed to minimise the deflection caused by loads; particularly the deflection that leads to buckling. Shear stiffness is especially important for resisting torsion. In fact it can be said that the ratio of the shear to the bulk modulus is a measure of solidity. By allowing large deflections to occur, plastic flow can lead to instability and failure, and the most effective way to avoid plastic flow is to have a low dislocation mobility in a material. Finally fracture requires cracks, and cracks represent the formation of new surfaces, so they are more difficult to form if the surface energy is high. In relation to considerations made above the properties and performances in specific applications of diamond and DLC coatings will be critically analysed.

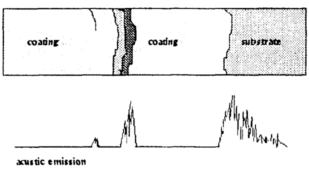
2 Applications of super-hard coatings

Progress made in the field of CVD diamond has enabled diversified mechanical applications of these coatings. There are several mechanical devices whose performance depends on the absolute strength of the material from which they are constructed; some depend on the weight specific strength and a few on the volumetric specific strength. Diamond belongs to the first category. Examples are[4]: ultracentrifuges; containers for magnetic, mechanical and electrostatic fields, and devices for storing power such as flywheels, or for controlling power such as rocket engines. They have been used for very demanding cutting (ultramicrotomes) and shaping (wire drawing) operations for a long time. Their use for containing mechanical fields (diamond anvil pressure vessel) is relatively recent.

A common material for overcoat protection is amorphous carbon[5]. Hydrogenated-carbon films are generally much harder than their pure carbon counterparts, but exhibit mechanical properties which depend on the hydrogen content[6]. On the other hand the DLC is similar to diamond in terms of mechanical strength and abrasion resistance and is expected to provide a wide range of applications as a high value added functional material. In addition DLC films are generally smooth and free of pinholes compared to diamond, hence they are expected to be applied to new fields, such as a variety of protective films, sliding parts, tools. These properties are important in applications where wear or repetitive contacts with the film may occur[7]. Conventional magnetic hard disks are composed of multilayer thin films deposited on rigid substrates. During normal hard disk operation, a slider with active magnetic read-write elements flies above the disk and occasionally makes contact with it. To prevent contact damage and wear in the relatively soft magnetic layer in which data are stored, hard overcoats are usually employed in the disk structure. Endurance of the carbon coatings is important, and it has been shown that magnetic recordings heads modified with DLC film maintain a low coefficient of friction for thousands of cycles, exhibiting excellent durability[8].

In general DLC suffers from three significant shortcomings which have impeded its application[9]: (1) it is always under very high compressive stress and this stress increases in proportion to hardness; (2) it is thermally unstable; it begins to revert to graphite and loses its desirable properties during prolonged exposure to temperatures roughly above 250° C; (3) the very low friction coefficient (less than 0.1) and wear rate of amorphous hydrogenated carbon are obtained only in very dry condition which cannot be assured in most applications. At high humidity, friction and wear of DLC increase so much as to leave it only comparable to a variety of other coatings.

Ultra low wear coatings also allow "surface engineering" for improved performance and durability, and enable the use of new light weight or low cost materials. The research in this field is a matter of great interest, particularly in the aerospace industry. Titanium and Ti-6Al-4V were studied[10] as substrates for diamond deposition in order to obtain high strength to weight ratios in airframes and as blades, discs and inlet guide vanes in gas turbine jet engines. Titanium is a strong carbide former, hence good adhesion is possible on diamond. Recently E. Buccioni et al.[11] studied and discussed key processing parameters affecting the film structure and the film/substrate adhesion in HFCVD of diamond films on titanium and Ti-6Al-4V substrates. Increasing hardness values were measured from the substrate towards the film and a multi-step process leading to the effective film detachment was observed during the scratch test (see fig.2). Adhesion tumbling occurred on films deposited at about 750°C, in the critical temperature range for transition in interface composition form a TiH_2 rich interlayer to a tick (about 100 μm under a film of few microns) TiC interlayer. Although the titanium alloy showed better hardness performances than the pure titanium (see fig.3), the adhesion of the film to the substrate was similar in both materials studied[11].



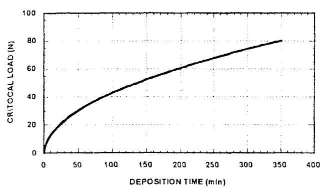


Figure 2: a) Schematic showing scratch test: the top part shows the trace left by the diamond tip; the bottom part shows a diagram of the acoustic emission. The first two peaks correspond to partial detachment points before the definitive detachment; b) Critical load of films deposited on a titanium substrate for different deposition time[11].

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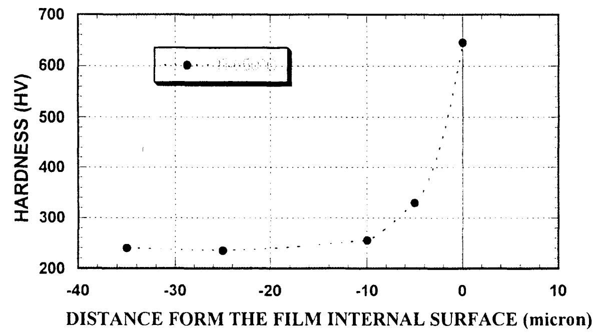

Figure 3: Hardness near the interface of specimens with different deposition temperature and substrate. The zero point corresponds to the internal side of the film[11].

3 Metal forming and cutting tools

Potential and market mature mechanical applications of CVD diamond fall essentially into the following categories: tools and mechanical components. Diamond has unique properties for tooling applications because of its high compressive strength (greater than 110 GPa), thermal shock resistance (ΔT higher than 1000 K) and high hardness (10 kHV), which results in an extremely high wear resistance. For this reason grinding, and cutting, ranging from rough cutting of stone and concrete to ultra-precision machining of electronic ceramics with reduced lubrication requirement have been considered as first possible applications of CVD diamond.

The utilisation of new materials extremely abrasive and wear resistant, such as hyper-eutectic aluminum-silicon alloys and glass fibre reinforced plastics in automobiles and electrical products, requires new cutting tools. Early efforts to process these materials using conventional machine tooling demonstrated to be cost prohibitive because of short usability and unpredictable failure of the cutting tools, hence the demand for diamond-coated tools experimentation. Presently the research on CVD diamond coatings for such applications concentrates on controlled nucleation, adhesion and surface roughness. The most important technical problem to be solved is the low adhesion of diamond on materials commonly used in these applications, including WC-Co, which is mainly due to different film-substrate thermal expansion coefficients. The general hardness-toughness relationship for cutting tools is shown in fig.4. Going from steel to sintered CBN or diamond, tools become more wear resistant, but less tough, and much more expensive. Benefits are obtained by combining tough substrates with hard wear resistant coatings. Besides cemented carbide cutting tools, also diamond coatings of Si_3N_4 and steel tools are investigated as well, but face difficulties in nucleation and adhesion. To improve the adhesion issue metallic interlayer, with good bonding to both steel and diamond, were proposed[12].

Currently diamond can be used for machining materials of very different natures[13], including aluminum-silicon alloys, copper alloys, fibre-reinforced plastics, green ceramics and semi-sintered ceramics. Moreover, diamond is not suited for machining carbide forming metals such as Ti, V or Cr, nor for machining metals such as Mn, Ni, Fe, or Co, in which carbon forms a solid solution: at high temperatures the chemical interaction with the work-piece made of these materials accelerates the tool wear. Also temperatures higher than about 800°C represent problematic operation conditions because diamond tends to graphitize, losing its value as wear-resistant abrasive.

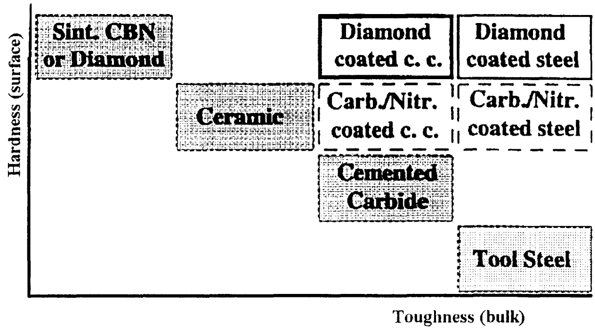

Figure 4: Hardness-toughness relationship for cutting tools[13].

In addition to its hardness diamond has a high coefficient of thermal conductivity, hence the heat developed during machining processes can be easily dissipated. Nevertheless, the surface roughness of as deposited CVD diamond can be much greater than that of the substrate. The roughness increase depends on the substrate surface structure, the coating thickness and the nucleation density[14]. The tribological properties of diamond films are influenced by several other factors, such as grain size and grain boundary strength, coating adhesion to the substrate and the presence of non-diamond inclusions which vary with the deposition conditions. Generally as-grown CVD diamond films are not suitable for tribological applications (surface roughness ranging from fractions of a μm to tens microns) without any post-treatment.

As matter of facts, the film quality is a subjective term and is related to the type of application. The required diamond coatings for tool inserts used for machining should have a desired graphitic content with well-faceted crystals, uniform grain size and coverage over flank and rake regions, and, of course, good adhesion with the substrate. The morphology at the cutting edge of a tool insert must have minimum defects, and diamond faces should be, as much as possible, aligned with respect to the cutting edge. Acceptable growth rates should also be guaranteed, hence, often compromises have to be made in the choice of the deposition parameters through an optimisation process.

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Metal working tools operate most often with intensive friction between work-piece and tool. If cutting tools can operate with as coated surfaces, metal working tools operating under strong friction, on the contrary, must have smooth polished surfaces. Because of its extreme low friction (generally quoted below 0.1) together with high hardness, diamond is a perfect material for coating metal working tools; both cemented carbide and steel substrates can be used. The following difficulties should be resolved: (1) the as coated surfaces are too rough and there is need for polishing, (2) there are adhesion and nucleation problems as with the cutting tools. When steel substrates are used, the elevated CVD temperature constitutes a risk for tool distortion, and in addition there is need for heat post treatment. CVD diamond coatings of cemented carbide wire bonding tools are also being developed to be used in the manufacture of integrated circuits[13].

In 1995 Kobe Steel Ldt. succeeded in the development of the first diamond-coated drill made of tungsten carbide[15]. In twist drills, a diamond film is deposited only around the cutting edges with thickness of 10-25 mμ. The deposition of a thick diamond film is not recommended for high quality surface finishing because the surface of the as-deposited diamond film is relatively rough, due to the grain growth occurring as the film thickness increases. The efficiency in drilling of such tools resulted highly increased, with an improvement in tool life more than ten times, together with good size stability and quality of processed holes. The resulting hole roughness can be less than 1 mμ [16].

Sintered diamond bodies are considered excellent abrasion resistant materials. A sintered body is fabricated by melting diamond grains along their boundaries at high pressure and temperature at which diamond is stable, then combining resynthesized diamond. This produces a firm, homogeneous body of connected diamond grains which is difficult to cleave and is particularly suitable as resistive material for dressers, drawing dies and bits. Yoshikawa et al.[17] first proposed and studied CVD sintered diamond as alternative diamond source.

The combination of diamond hardness and wear-resistance, and the high gap in energy between the conduction and valence band (2eV) suggested applications also in optics. Diamond thin films can be deposited on windows and lenses to make them scratchproof and non-reflecting while ensuring a high transparency to radiation whose energy is lower than the gap between diamond energy levels.

4 Mechanical components

The hardness, wear resistance and low friction of diamond make this material ideal for slide, roller or ball bearings. Needs for surface engineering of rolling and sliding mechanical components fall into several broad categories: (1) reduction of wear in heavily loaded, lubricated contacts, (2) reduction of both friction and wear in situations where lubrication is limited or even undesirable,

(3) reduction of friction and wear of materials that while strong, are tribologically poor and (4) modification of light weight materials (Al, Mg) for improved durability in mechanical applications (see below). For these applications the required characteristics of diamond coating are: low friction, good adhesion and extremely low surface roughness.

Liu et al.[18] proposed a wear mechanism to describe the low friction of DLC films which is based on the transformation of DLC to graphite. The transformation is related to the frictional energy and includes two stages: hydrogen release from the structure causing lattice relaxation and shear deformation of the DLC structure producing graphite. For an ideal tribocoating a conformal and very smooth coating is desired for automotive applications, and not be prone to cleavage: these two virtues are intrinsic to amorphous materials.

Advanced bearing technology took advantage since several years[19] of CVD TiC coatings on bearing balls. Since diamond is harder than TiC, and has a lower friction than TiC, thin diamond films on bearing balls are expected, under certain circumstances, to perform even better. In this sense titanium carbide (TiC) coatings can dramatically improve the service life of miniature precision ball bearings. Research and development work in this direction is going on. The performance enhancement achieved by diamond coatings is achieved by the combination of high hardness and low coefficient of friction. The main aim of the research is to measure the coefficient of friction[19] of flat or near flat diamond in the sliding regime against the more conventional substrate materials in order to estimate the value of hardness during indentation tests. In particular Yurkov et al.[20] demonstrated a load dependence of the coefficient of friction in dry sliding regime between a diamond cone on steel, sapphire, alumina and fused silica. In particular friction of diamond on steel decreases considerably using a lubricant with a slightly acidic nature. The limitations here are the need for an extremely smooth polished surface (better than 5 nm), and the possibility of chemical reaction between diamond coated balls and steel raceways.

As indicated by Robertson[21] there are two dominant wear mechanism: abrasive wear and adhesive wear. The accepted correlation of wear resistance with hardness suggests the use of ceramic carbides and nitrides, with diamond being the ultimate anti wear coating. In this sense Tamor[9] measured friction against steel of a wide range of materials as a function of their hardness. As shown in fig.5 the softest materials exhibit low friction but because they shear within themselves, they are also high wear materials.

For sliding of ferrous alloys on themselves, friction is high and liquid film lubrication is usually used. For ceramics and hard amorphous hydrogenated carbon (a-C:H), friction is also low, but unlike for the soft materials, wear is also low. In effect the easy shear of the solid film lubricant is achieved, with the shear always occurring at the original contact surface. Thus the surface morphology of CVD diamond is of critical importance for the tribological performance of diamond coated bearings.

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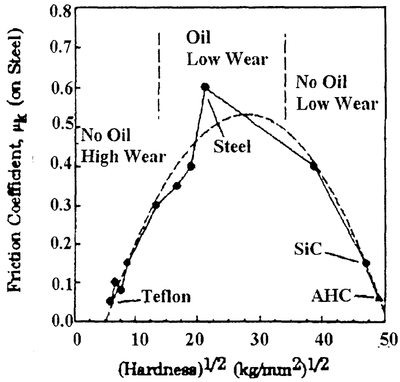

Figure 5: Friction of various materials sliding against steel as a function of hardness. The dashed curve is a parabola fit to the data to emphasise the trends[9].

Another important application for micromechanical parts is the coating of indenter tips of scratch tester equipments used for measuring adhesion of a coating to a substrates. These tips are usually made of single-crystal natural diamond but they have a short lifetime due to their tendency to be cleaved, and measured values of adhesion have large scatter. Since CVD has a polycrystalline structure, its fracture tolerance is thought to be greater than that of single-crystal diamond and this observation suggested the replacement of natural with CVD diamond tips. In this sense Takeuchi et al.[22] proved that polycrystalline diamond has longer life and found that, thanks to the fact that CVD diamond does not have particular crystallographic orientation, measured values of critical loads do not depend on scratching direction, as happens for single-crystal diamond indenters.

5 Mechanical properties of coated fibres and wires

The continuous effort to develop new materials with improved properties has sparked an interest in diamond-coated fibres and wires, which is ever increasing due to many prospective applications. One of such applications is in the production of composites for aerospace applications. In the aerospace industry, rigidity and weight savings are of concern, consequently lighter, stronger, stiffer materials are always in demand. Patridge et al.[23] found that a substantial increase in fibre Young's modulus can be expected by diamond coating existing reinforcement fibres. An average fibre modulus of 874 GPa was calculated for diamond, which is more than a factor of two greater than for SiC fibre. Such diamond-coated fibres have measured modulus values close to that expected for bulk diamond, making them extremely stiff for their weight.

The properties of a diamond coated fibre can be modified by selecting a suitable core material. There are four major requirements for the core material: a surface that encourages diamond nucleation; adequate chemical stability in the activated hydrogen methane gas mixture used in the diamond deposition process; adequate mechanical strength to withstand a deposition temperature of 900-1000° C; and thermal expansion compatibility with diamond. Recently diamond fibres have been manufactured by CVD on thin metallic wire or ceramic cores. A SiC fibre or a tungsten wire satisfies these requirements[24], with the latter initially forming a thin stable tungsten carbide layer. In general SiC fibres incorporated in Ti alloy, or Ti aluminide matrices, already in use in the aerospace industry, can lead to significant improvements in specific strength and stiffness of components at ambient and elevated temperature, with predicted[25] weight savings up to 75%. Diamond fibres coated with titanium alloy and then consolidated into a composite, can comprise up to 85% diamond. For these composites a modulus of about 750 GPa can be predicted using the rule of mixtures, which is 3-4 times that of current Ti-alloy/SiC fibre composite with about 30% fibre volume fraction. The choice of the wire material, residual stresses in diamond, diamond surface roughness and interface greatly affect the tensile stress of the fibre. The diamond fibres with a Pt core resulted much less brittle than the corresponding W-core fibres. This was attributed to a thin graphite layer between the core and the diamond which allowed easy interface and decohesion without stressing the diamond coating and allowed plastic deformation of the Pt core[25].

Diamond deposition is more difficult on metallic fibres that form solid solutions with carbon such as iron[26], nickel, and titanium. Nevertheless deposition of diamond on ferrous materials is of particular interest, because of their low cost and widespread use. Furthermore, a ferrous wire core would be an attractive low cost, low density alternative to tungsten wire cores for diamond fibres. On the other hand, diamond films deposited directly on steel exhibit poor adhesion and high residual stresses, which lead to delamination of the diamond coating. To avoid this problem, a number of inter-layers have been considered. In order to asses the potential of steel wires for fibre cores, diamond deposition has been carried out on titanium coated iron and iron-chromium wires. In this sense Partridge et al.[24] found that titanium coated iron and iron-chromium wires can be coated with diamond by chemical vapour deposition, but after depositing for 40 h the fibre cores were converted to very hard carbide microstructures. During the cooling of straight diamond coated wires, thermal stress cracking of diamond was avoided by stress relief cracking in the disordered graphite layer at the diamond/Ti rich layer interface. This effectively leads[24] to a hollow diamond fibre with a loose core, and with the fibre strength and stiffness determined by the diamond volume fraction only. This, together with diamond's fairly low density, may lead to significant weight savings. In addition, its extremely high thermal conductivity widens the scope of applications for such a product.

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High stiffness composites made with diamond coated fibres were also studied for ductile grinding. Experiments showed that diamond fibres can be used to grind glass under ductile flow conditions with less critical conditions and without brittle surface cracks associated with conventional abrasive grinding of glass[27]. This result was supported by the observation of the ease with which very low surface roughness values could be obtained on alumina by CVD diamond fibre grinding. Recent studies indicated also that the final stage of polishing of optical lenses may be substantially reduced or omitted completely by ultra precision single-point or line contact diamond grinding. This was considered to be an important result as the polishing final state is often very time consuming and expensive, as is the case of ceramic, optical materials and silicon.

6 Erosion behaviour of diamond

Of the thermal properties both the thermal conductivity and thermal expansion coefficients are important for high velocity aerospace applications, since these properties (along with fracture stress, Young's modulus and Poisson ratio) determine the thermal shock resistance of the material, which is exceptionally high in the case of diamond. On the other hand, the low thermal expansion coefficient, while aiding thermal shock resistance, can in one case in particular have the opposite effect on erosion resistance. This is the case of diamond coating on existing aerospace substrates. The combined effects of micrometeoroids, atomic oxygen, solar radiation, and ionised particles, can degrade the properties of the coatings well before the substrate structure has outlived its usefulness. Consequently, there is a need for the development of advanced survivable materials coating to extend the useful life of space components. Recently R. Rameshan et al.[28] found a specific application in the aerospace erosion for high flight velocities such those that would be experienced by a missile or a jet aircraft. The probability of damage caused by the micrometeoroids particles increases as the spacecraft size increases. Therefore, it is appropriate at this stage to develop transparent, non-reflective surface coatings to protect various external surfaces of the spacecraft from impact damage by micrometeoroids and debris particles. All the coatings should be mechanically adherent and resistant to hypervelocity impact events. In general the major problem is with the adhesion of the coating to the substrate. The low thermal expansion coefficient of diamond means that as the sample cools from the high deposition temperatures the substrate contracts far more than the diamond and its upper surface is put into tension. The thermal stress has two consequences. The first is that the fracture stress of the substrates is reduced (in extreme cases the sample fractures as it cools). The second is that the coating will more easily delaminate.

Materials, such as zinc sulphide and germanium[29], have extremely low resistance to sand particle and raindrop impact and this can be a limiting factor in the performance of a missile. Diamond is therefore being considered as a

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coating material for the existing substrates or, ideally, as a bulk window. Perhaps surprisingly the exceptionally high hardness of diamond does not, in itself, dictate that the material will have an exceptionally high sand or rain erosion resistance. It is true that for good sand erosion performance a material must have a hardness higher than that of the erodent so that the incoming projectile is defeated. If the target hardness is sufficiently high then there will be little or no ductile deformation in the target and the material fails through a purely elastic, brittle mechanism (fig. 6). In this case the threshold velocity for damage is determined by the material's fracture toughness rather than its hardness. Rain and sand erosion studies evidence both intergranular and transgranular fracture, suggesting that the grain boundaries are quite strong. It is clear, however, that the grain size is a crucial parameter when considering the erosion resistance of CVD diamond and indeed many of its other properties. As discussed by Field et al.[29] it is primarily the fracture toughness to determine the extent of damage in brittle materials exposed to the condition of sand erosion. Diamond's high fracture toughness therefore gives it a high resistance to sand erosion. In the last years it is tempting to use thin CVD diamond samples if at all possible, but the damage mechanisms are thickness dependent and for thin samples they will greatly reduce their threshold velocities. This a particular problem in the case of diamond because of its high modulus and consequent high stress wave velocity. Thicker samples are obviously desirable but, unfortunately, with current growth technology, the quality decreases as thickness increases.

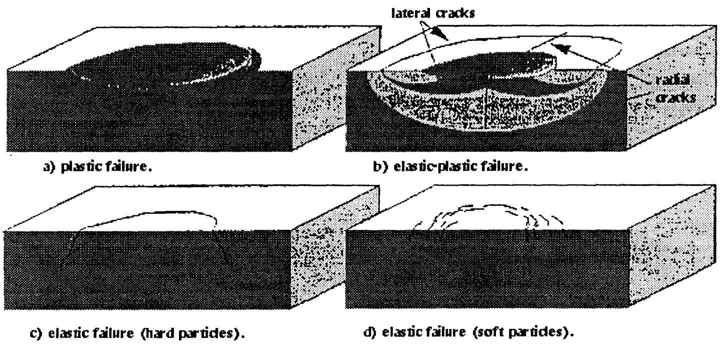

Figure 6: Damage mechanism observed after liquid and solid particle impact[29].

The deposition of CVD diamond films on the surface of windows for infrared transmission on airborne systems was also the subject of extensive research. In these applications diamond is used to improve the resistance to impact by water droplets or sand particles, which pose a serious threat in such systems[30]. A diamond film should be the ideal material for a protective layer as it is the hardest substance and is transparent over all wavelengths except for an absorption band in the 3-5 μm region. Alternatively free-standing diamond windows could be fabricated, but considerable effort would be required in polishing the scattering growth surface. The grain size at the film surface and backside is quite different due to growth competition of grains, hence also different mechanical properties are to be expected.

Chemical erosion represents another important degradation mechanism of materials. Diamond chemical inertness with respect to acids has been considered for applications in harsh environments. Nozzles coated with diamond were cast for use in diesel engines[31] as a protection to chemical erosion and a mean for polluting emissions reduction, by preventing reactions with the fuel to occur on the heated nozzle wall. Diamond nozzles were also tested for inserts used to inject cooling water into a gas turbine for protection against erosion from cavitation, thermal stress and corrosion from trace impurities in the water[32]. Generally, a passive film coating[33] is used as a physical barrier to protect a metal surface from exposure to moisture and other ionic species. Interconnection between the chips in a multi-chip module (MCM) is provided by thin metal lines, which are typically made of gold, aluminum, or copper. Corrosion of these metal lines is a major concern in MCMs. Plasma deposited amorphous carbon films with high thermal conductivity and chemical inertness are suitable passivation coatings provided that they are pinhole free and do not absorb moisture[33].

7 Future directions for applications

As the ability to grow diamond films on a wide variety of substrates becomes better known, new applications should arise, driven by the extreme properties of diamond. A host of application for vapour deposited diamond as wear resistant surfaces are likely to be realised soon. New applications should quicken the pace of research and development and will catalyse the process of technical innovation. Fabrication of diamond coatings, even at the currently high costs of production, could be jet well justified in environments where high temperatures and pressures, intense radiation, chemical each, and other adverse conditions can destroy materials.

A number of technological innovations that are required for future applications are briefly listed below. First of all the ability to grow large area heteroepitaxial films of diamond on non diamond substrates is not possible now. If achieved, this would open up a wide variety of mechanical applications. For well engineered tribosystems where substrate materials do not plastically deform under the designed loads and surfaces are smooth enough to prevent abrasive wear, effort should be devoted to understand and control the surface chemistry of the coating. Of the expanding plethora of hard thin-film coatings, silicon-stabilized amorphous hydrogenated carbon best approximates ideal tribocoating: it is slippery and wear resistant under a wide range of conditions - with the possibility of further improvement, reasonably stable, smooth - and may be deposited at low temperature at acceptably low cost. Diamond coating on tooling may also be expected shortly. Most of these applications require detailed, individual solution of specific bonding and interface problems. Deposition temperatures (about 1000°C) should be lowered in order to allow both low melting materials to be coated by diamond and to improve the film/substrate adhesion by a reduction of thermal stresses. The development of more sophisticated reactor modelling methods will be necessary for the optimisation and control of diamond vapour deposition processes. This could lead to greatly enhanced growth rates and enhanced uniformity of deposits. Modelling may also aid in developing better methods for producing conformal coatings on complex shapes.

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