Mechanical properties of polycrystalline diamonds

The room temperature mechanical properties of polycrystalline diamonds, i.e. tensile strength, transverse rupture strength, compressive strength, impact strength, fracture toughness, and elastic constants, have been determined. The applied test techniques are described and the results compared with those obtained by other authors. The fracture mode under the present experimental conditions was primarily transgranular. A grain size dependence, where strength increases with decreasing grain size, has been found. Fracture toughness was found to go through a maximum for grain sizes between 10 to 30 μm. The modulus of elasticity increases with increasing grain size. An influence of cobalt content on strength and modulus of elasticity has been found, while no significant influence on toughness could be determined. Increasing the cobalt content increases strength, but has the inverse effect on the modulus of elasticity. The results of strength, toughness, and elastic constants measurements are discussed in terms of available models and theories of polycrystalline ceramic materials. It can be seen from the results that polycrystalline diamonds behave in a manner similar to that of most engineering ceramics, but have the distinct advantage of a higher fracture toughness. *MST/596*

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Introduction

The mechanical and physical properties (e.g. hardness, elastic constants, wear resistance, and cleavage of single crystal diamond) of polycrystalline diamonds are highly orientation dependent. Crystals tend to cleave very easily along the weak planes which are the (111) or octahedral planes. In single point cutting tools or wire drawing dies, attention must be given to the orientation of the crystal to minimise the possibility of catastrophic cleavage or uneven wear. As for metals and ceramics, the presence of a fine, randomly oriented polycrystalline structure should improve toughness and this is indeed found for ballas, a naturally occurring polycrystalline diamond, which is extremely tough.

The diamond-to-diamond bonding required to overcome the disadvantages of single crystals can be achieved synthetically by sintering diamond powder under high temperatures and pressures in the presence of a suitable solvent/catalyst (usually cobalt). Such materials, referred to as polycrystalline diamond (PCD), and a special thermally stable non-solvent/catalyst variation using silicon as a sintering aid, are the subject of the present investigation.

Excellent performance characteristics have been shown by PCD tools in operations such as machining, dressing, wire drawing, and rock drilling. It has been found that the performance was sensitive to grain size and therefore particular attention will be focused on this parameter.

Kingery *et al.*,[1] for example, report for ceramics an increase in shock resistance with decreasing grain size. The same has been found by Bex and Robertson[2] when testing PCD material of various grain sizes. For their tests,[2] the testpieces were clamped in a standard milling head and used to flycut an extremely hard, abrasive granite. Horton and Horton[3] also report an increase in wear performance with decreasing grain size of PCD. Their test[3] consisted of turning a cylindrical piece of barre granite on a lathe which is a common test in the oil well drilling industry.

However, it has also been found by the same authors,[3] when turning aluminium alloys under extremely high wear conditions, that coarse grained PCD was substantially more wear resistant than finer grades. The same was found when lapping PCD. The fine grade wore about two and a half times more readily than the medium grain size which, in turn, wore about three and a half times more easily than the coarse grain sized material.

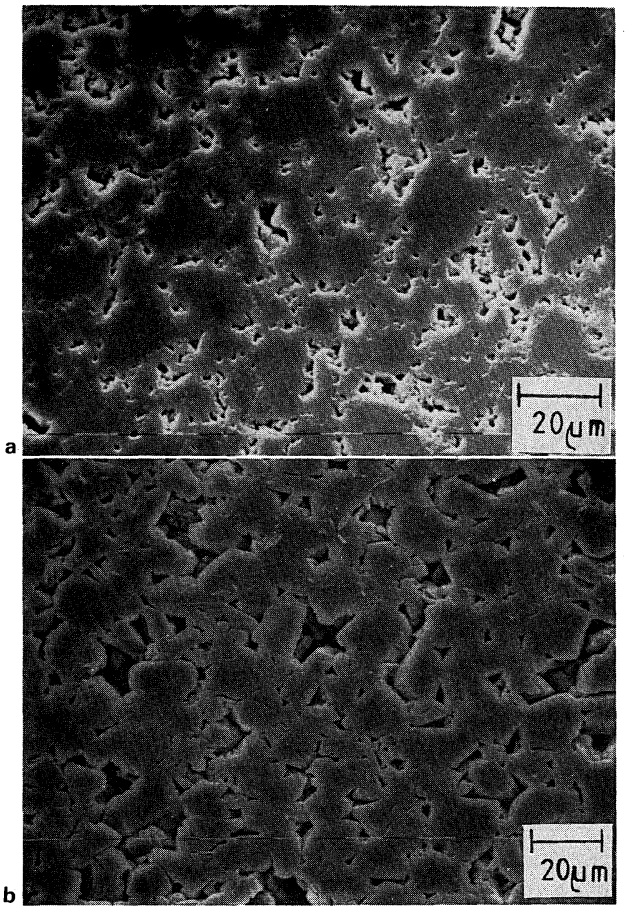
Not only wear behaviour is of interest; tool properties also influence the tool edge geometry for efficient cutting.[4] An understanding of the mechanism of wear and chip formation at the cutting edge of the PCD under different working conditions and workpiece materials can eventually lead to improvement in the ability to design tools. Thus, it is important to understand the behaviour of properties such as: transverse rupture strength (also referred to as flexural strength), tensile strength, fracture toughness K_{Ic}, and elastic constants.

Microstructure of polycrystalline diamonds

Although sintered PCD is a relatively new material, some understanding of the microstructural features and their relationship to macroscopic properties has been developed.[5–7] The structural characteristics of Syndite, a De Beers diamond composite, have been investigated by Pipkin and Wilson,[8] using X-ray diffraction and scanning electron microscopy. They found that during synthesis of PCD, plastic deformation is induced within individual diamond particles. True diamond-to-diamond bonding occurs to various degrees depending on sintering conditions and the sintering aid employed (e.g. *see* Fig. 1*a*). A mosaic substructure with a mean diameter of 0·09 μm was indicated by line broadening measurements on X-ray diffraction patterns. This substructure is considered important in enhancing the toughness of these materials.

Substructures in other PCD materials have more recently been ascribed to the presence of deformation microtwins.[6] Various authors have observed this phenomenon in natural diamonds[9] and in naturally occurring aggregates called framesite.[10] Under semihydrostatic conditions, as might exist in the presence of a softer phase, the deformation structure will probably not be generated uniformly throughout the compacted aggregate. Walmsley and Lang,[11,12] as well as Yazu *et al.*,[13] found this by examining thin foil samples of PCD in a transmission electron microscope.

According to standard liquid phase sintering theory, the role of the cobalt metal is twofold. First, it dissolves any



a material E; *b* material H

1 Photomicrographs of material E and H (*see* Table 1) after etching out secondary phases: different degrees of diamond/diamond bonding can be seen

graphite formed in the early stages of the synthesis cycle which subsequently reprecipitates in the form of diamond. Second, it rounds-off sharp corners of the grains and the necks between bonded diamonds and therefore reduces their effect as stress raisers.

It can be inferred from measurements of axial and surface electrical resistivity made by McLachlan,[14,15] that an idealised model for the structure of Syndite could be termed a 'builders' scaffold' or 'lumps and threads'.

Experimental details

Samples of materials A–D (*see* Table 1) were produced as composites, i.e. with the diamond layers bonded to cobalt cemented tungsten carbide substrates. The carbide was removed before testing. Samples E–G were specially prepared as unsupported PCD discs and sample H was produced with SiC instead of cobalt as matrix.

A universal testing machine (Instron 6000), using load cells matched to the expected failure load, was employed for all mechanical testing except impact testing, which was performed on an impact hammer (Avery).

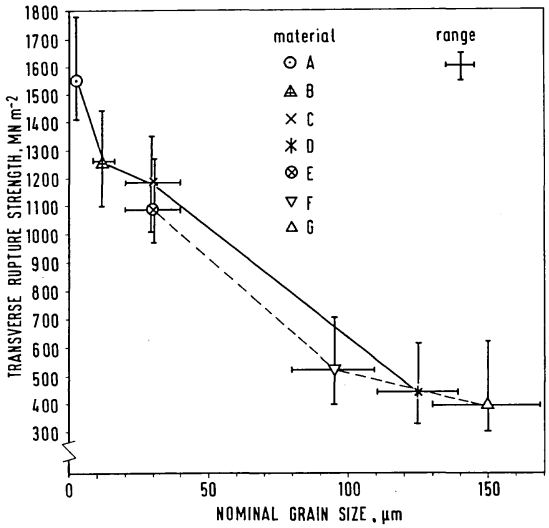
The transverse rupture strength measurements were carried out in three point bending, using discs (*see* 'Results and discussion') ground to a nominal diameter of 12 mm. Samples A–D were tested at a thickness of only 0·8 mm, because of their method of manufacture, while samples E–H were 2·5 mm thick. For consistency, the surfaces of all samples were lapped using 200–400 US mesh diamond grit, which gave a surface finish of 0·3–0·5 μm.

A diametral compression test, which is generally used to determine the tensile strength of concrete, rock, glass, and ceramics,[16] was used for samples E–H. They were tested by loading between two PCD anvils, shimmed with a copper foil to prevent spalling. The specimens were 13 mm in diameter and 2·5 mm thick.

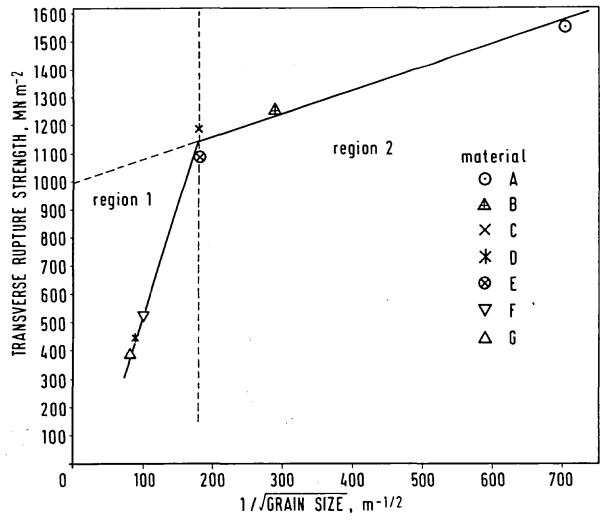
Table 1 Parameters of materials A–H under investigation

	Co matrix PCD supported by WC–Co				Unsupported Co matrix PCD			Unsupported SiC matrix PCD	
Parameter	A	B	C	D	E	F	G	H	Total no. of measurements*
Nominal grain size, μm	2	12	30	125	30	95	150	22	...
Matrix (Co or SiC) content, vol.-%	13	11	11	12	5	6	5	19	...
Density, Mg m^{-3}	4·24±0·10	4·12±0·09	4·10±0·11	4·15±0·10	3·77±0·12	3·83±0·06	3·79±0·12	3·43±0·08	144
Longitudinal speed of sound, m s^{-1}	13361±462	13812±800	14130±658	14368±786	15517±165	15402±242	15914±164	16570±150	...
Transverse speed of sound, m s^{-1}	...	...	...	...	10520±143	10456±188	10820±172	11152±180	72
Transverse rupture strength† (TRS), MN m^{-2}	1550	1256	1188	444	1090	520	389	1044	144
Weibull modulus	3·38	4·25	4·41	3·44	3·21	3·95	4·12	4·60	...
Tensile strength, MN m^{-2}	...	...	...	...	1543±209	301±140	344±76	525±255	40
Compressive strength, MN m^{-2}	...	...	...	...	4678±1241	2475±867	1947±641	4192±1337	120
Fracture toughness, MN m$^{-3/2}$	6·86±0·43	8·81±0·46	8±89±0·37	7·49±0·78	9·11±0·42	7·51±0·21	6±99±0·64	6·89±0·37	32
Fracture surface energy, J m^{-2}	31	50	49	33	46	31	26	26	...
Poisson's ratio	0·070	0·070	0·070	0·070	0·075	0·070	0·073	0·086	...
Young's modulus, GN m^{-2}	749	776	810	849	897	897	953	925	...
Shear modulus, GN m^{-2}	350	363	379	396	417	419	444	426	...
Bulk modulus GN m^{-2}	290	301	314	328	352	348	372	372	...

* Total no. of specimens tested was 408.
† Also referred to as flexural strength.



2 Transverse rupture strength *v.* nominal grain size for materials A–G



3 Strength *v.* grain size relationship for PCD

For uniaxial compression, cubes 3 × 3 × 3 mm were used. These cubes were laser cut from 3 mm thick lapped discs, and loaded on the lapped faces during testing. Again, PCD anvils were used and only materials E–H were tested.

Fracture toughness measurements were obtained for all materials. The test configuration was the same as that used for the diametral compression test. The specimens were o.d. ground to 4 mm dia. and lapped plane parallel to a thickness of 0·8 mm. A central slot 2 mm in length was cut using a pulsed YAG (yttrium–aluminium–garnet) laser.

Impact tests were carried out on materials A–D. The samples were 12 mm dia. discs, 0·8 mm thick.

Density values were obtained using the specific gravity bottle method for samples A–D and by volume and weight measurements for the much larger samples E–H. These measurements were subsequently used to calculate cobalt contents, assuming all materials to be fully dense.

Velocity of sound measurements were carried out using a pulse–echo technique, on a pulser–receiver unit with a digital wall thickness measurement module (Krautkrämer USIP 12). For samples E–H, the longitudinal speed of sound was measured using an immersion technique with a 20 MHz probe, while the transverse speed of sound was measured with a 10 MHz contact probe. On materials A–D, only longitudinal speed of sound measurements were carried out because of sample thickness constraints resulting from their method of manufacture.

Results and discussion

TRANSVERSE RUPTURE STRENGTH TESTS

Usually, strength is assessed by measuring the TRS of a bar in bending, because it its easy to perform and it reveals selectively the worst flaws present in the stressed volume. Because PCD products are usually produced as discs, Roberts[17] carried out theoretical investigations of a disc specimen in three point bending. He found that it is theoretically permissible to use disc shaped specimens to determine TRS, and this approach is adopted in the present work. As with every other brittle material, the rupture strength of PCD is a statistical quantity. Therefore, variable sizes, shapes, and orientations of the flaws in the material can account for the observed scatter in fracture strength. A statistical method commonly used to determine the strength values of brittle materials is that given by Weibull.[18,19]

The results observed for the various materials are given in Table 1 together with the nominal grain size of the materials. The Weibull modulus for the different materials varied between 3 and 5, which is as expected for such brittle materials. For ceramics, it varies between 3 and 8. A plot of TRS versus grain size is shown in Fig. 2.

For a given grain size, samples containing a silicon carbide matrix were weaker than their cobalt containing counterparts. This decrease in strength has also been found by Gigl,[20] who interpreted it as a result of poor bonding between the diamond particles as a result of the difficulties of diamond-to-diamond bonding without the benefit of catalysed growth. This has been confirmed by Pipkin[21] who showed that etching out the matrix (Fig. 1*b*) significantly reduces the strength of PCD manufactured with a silicon carbide matrix. Gigl showed that dissolving the cobalt matrix of a catalytically sintered PCD material will also reduce its strength, but not as drastically as for a non-catalysed material.

Results obtained by processing experimental data on the variation of TRS with grain size for PCD revealed the existence of two characteristic regions (Fig. 3). These results are in good qualitative agreement with those obtained for other absolute brittle materials, such as MgO, Al_2O_3, BeO, and B_4C (Refs. 22–24).

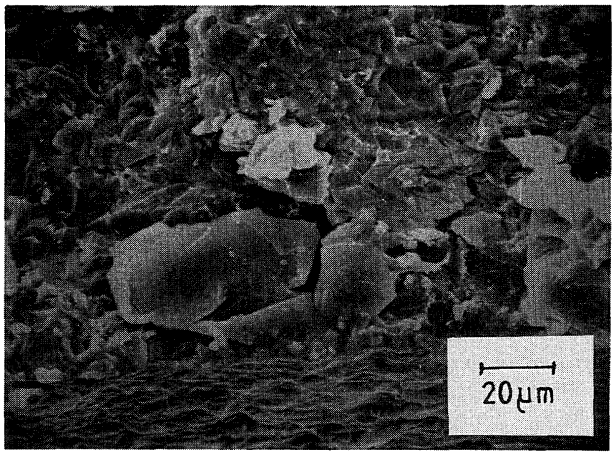
To explain the appearance of the curve, two models are available. Camiglia[22] suggested that for region 1, which follows the classical Griffith–Orowan strength relationship

$$\sigma_f = K_1\sqrt{d} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

(where σ_f is the strength, K_1 is a constant, and d is the average grain size), for some polycrystalline ceramic materials, the largest grain size is the most severe flaw leading to failure. The failure mechanism consists of propagation of these existing flaws.

Using SEM, PCD fracture surfaces have been examined to check this theory. By tracing back the river patterns, the fracture origin can be identified. In some cases, single large grains close to the tensile surface of the three point bend specimen (e.g. *see* Fig. 4) were found.

The mode of fracture of these coarse grained areas ($\geqslant 30$ μm) is transgranular. Very often the fracture path does not even change direction at the grain boundary, but follows the direction of maximum tensile stress regardless of crystal orientation. Occasionally, some internal flaws, such as poorly bonded grains or a defective crystal, caused failure.



4 Large grain as fracture origin in TRS specimen

At region 2 for small grain sizes ($\leqslant 30$ μm), the strength follows the Hall–Petch strength relationship

$$\sigma_f = \sigma_0 + K_2\sqrt{d} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where σ_0 and K_2 are constants and d is the mean grain size. In that region, the mechanism generating flaws is based on microplastic flow nucleated fracture caused by dislocation processes. In the application of this equation to fine grained materials it is assumed that the microplastic flow or dislocation activity leads to crack nucleation.

Although plastic deformation at room temperature has been observed under high pressure, this type of failure model seems to be unlikely for PCD. However, grains which clearly had slipping bands indicating plastic flow and microcracks were revealed by SEM. An example is shown in Fig. 5, in which the continuity of slip bands across the crack indicates that it is an internal crack and not a grain boundary defect. However, it was not possible to establish how the deformation and the crack had been generated, i.e. if it was during high pressure sintering, cooling, or testing. Further work will be necessary to clarify if equation (2) can be used to describe the strength of fine grained PCD material.

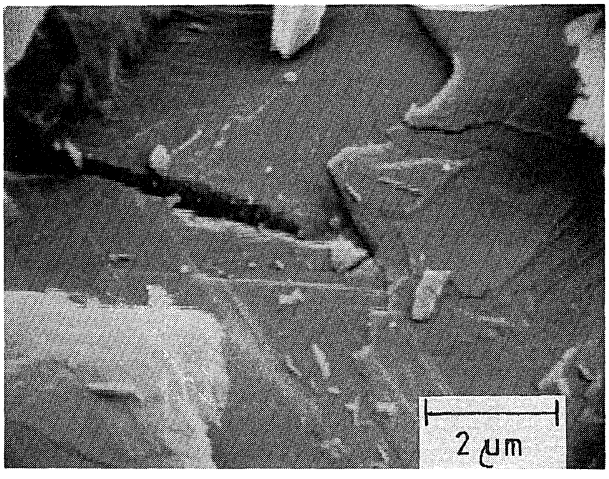
A similar explanation for the strength dependence on grain size was given by Rice[23] in regard to a large body of data in the ceramic literature. However, he later suggested that the bimodal nature of the curve was a result of the crack size c versus grain size d relationship.[40] He showed that in several ceramics the inherent flaw (probably introduced during machining and surface finishing operations) was generally independent of grain size. Consequently, for coarse grained material with flaws introduced through machining, the crack size/grain size ratio is smaller than for fine grained material. Therefore, for fine grained materials σ_f is controlled by the polycrystalline fracture surface energy. For coarse grained material, according to Rice, σ_f is controlled by the single crystal surface energy, since the flaw is contained within a single grain. Thus, when the critical stress intensity factor corresponding to the single crystal is reached, the crack would begin to propagate and lead to failure without arrest. According to that theory, the transition grain size occurs at $c \approx d$. A calculation of the critical crack length based on the measured values of fracture toughness, strength, and elastic constants is given in Table 2. From that calculation, it can be seen that the critical ratio of $c/d = 1$ should be reached between 12 and 30 μm, which is indeed the case as can be seen in Fig. 3. Therefore, it appears that this type of interpretation of the bimodal strength distribution is more suitable than that of Camiglia.

Table 2 Calculation of critical crack length

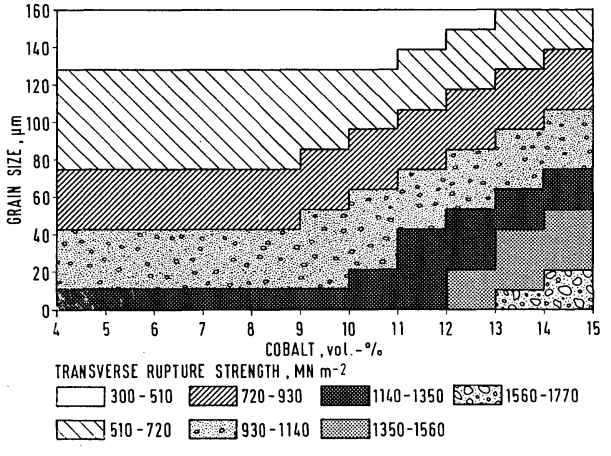
	A	B	C	D	E	F	G
c_{crit}, μm	6	16	18	91	19	68	105
d, μm	2	12	30	125	30	95	150
c/d	3·00	1·33	0·60	0·73	0·63	0·72	0·70

Since PCD is a two phase material, it was also of interest to determine the influence of the secondary phase on TRS. However, it must be stated that the cobalt content cannot be changed systematically for a given PCD grain size since it is introduced by infiltration rather than by admixing. Therefore, it is of a statistical nature and varies over a wide range for different PCD materials. The cobalt content was calculated using the measured density and assuming full density was achieved during sintering.

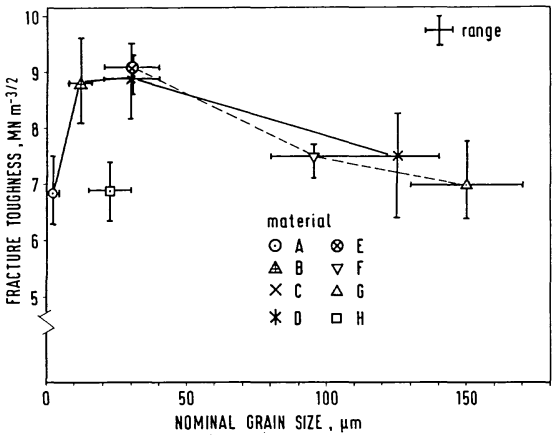
The average values obtained, which depend on how the material was produced, are given in Table 1. However, two mean levels of cobalt content were achieved, each having a wide spread. An analysis of variance based on a random model indicated the influence of the cobalt content for materials C and E. Since all three properties, TRS, grain size, and cobalt content, are statistically distributed, a three dimensional statistical curve fitting procedure (SAS) was used to find trends of the influence of cobalt content and grain size on TRS. The results are shown in Fig. 6 and based on 126 points of measurements of the three



5 Fractured grain showing deformation bands and microcrack perpendicular to fracture plane (SEM)



6 Transverse rupture strength as function of grain size and cobalt content for materials A–G



7 Fracture toughness *v.* grain size relationship for materials A–H

properties for materials A–G. A tendency towards the relationships TRS directly proportional to cobalt content and inversely proportional to grain size is indicated.

DIAMETRAL COMPRESSION TESTS

The diametral compression test is generally used for measuring the tensile strength of rock, coal, polymers, and ceramics.[25] It is based on the state of stress developed when a cylindrical specimen is compressed across a diameter between two opposing anvils. For the ideal case of line loading, the maximum tensile stresses, which act across the plane containing the lines of loading, have a constant magnitude given by

$$\sigma_t = \frac{2F}{\pi D t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where σ_t is the maximum tensile stress, F is the applied load at fracture, D is the specimen diameter, and t is the specimen thickness. In practice, two problems arise. First, the thickness/diameter ratio of the sample must be decided, since a disc that is too thick becomes a cylinder which has a different mode of failure because of its axial stress. On the other hand, failure by buckling occurs in discs which are too thin. Obviously, this again is not a pure tensile failure.

The second problem is that the specimen can spall at the loading point owing to the contact stresses present. To overcome this problem, copper shims were used. The failure modes can be recognised by examining the fractured specimens. Normal tensile failure, the desired mode, is illustrated by a simple halving of the specimen along the loaded diameter. Triple cleft fracture is a variation of normal tensile fracture and it has been found that it is valid to use samples exhibiting this fracture mode to calculate tensile strength.[16]

This mode was the only fracture pattern occurring with varying degrees of fragmentation. In some instances, there was substantial fragmentation. This explosion type of failure has also been observed when testing ceramics. The fracture stresses calculated using equation (3) are given in Table 1 for the various materials tested. The Weibull theory was applied to determine mean values, but this concept does not fit the observed values as well as for the TRS data. Therefore, averages and standard deviations were calculated. The strength decreased with increasing grain size, and strength values of the non-solvent/catalyst sintered samples were lower than those of the cobalt infiltrated samples.

FRACTURE TOUGHNESS TESTS

The ability of materials to resist fracture is usually assessed by linear elastic fracture mechanics techniques, but the conventional methods for determining fracture toughness cannot be employed for testing PCD, since it is difficult to produce specimens large enough.

Two techniques have been used to test the fracture toughness of diamond. In the first, K_{Ic} is obtained either by Vickers indentation[26–28] or from a Hertzian test using a blunt indentor.[29] Second, according to Yarema,[30] a disc with a centre crack may be used as a K_{Ic} specimen for PCD. The disc is loaded in diametral compression and K_{Ic} values are calculated using

$$K_{Ic} = \frac{1{\cdot}01227F}{t(\pi R)^{1/2}} \left(\frac{\lambda}{1-\lambda}\right)^{1/2} \times (1 - 0{\cdot}6038\lambda + 1{\cdot}672\lambda^2 - 1{\cdot}698\lambda^3) \quad . \quad . \quad . \quad . \quad (4)$$

where $\lambda = 2L/D$ is the ratio of the notch length to the specimen diameter, R is the specimen radius, t is the specimen thickness, and F is the load at fracture.

Devin *et al.*[31] used this type of specimen to determine the fracture toughness of both PCD and a WC–6Co hardmetal. Magnetic and non-magnetic diamond grits were used in the PCD and these gave values of 6 and 5 MN $m^{-3/2}$, respectively. No information concerning grain size and binder was given. The value for the hardmetal was about 5·9 MN $m^{-3/2}$, which seems to be low compared with reported values using other methods and also to values obtained for similar materials by the present author, using this method.

For the K_{Ic} test, using a disc specimen, similar problems are encountered as for the tensile tests. The thickness/diameter ratio must be correct, otherwise the sample buckles and does not fail in a pure tensile mode. The other problem arising is the minimum specimen size. However, in current tests on ceramics and material H, a diameter/thickness ratio of 5 gave consistent results when reducing the diameter from 12·5 to 4 mm. The results obtained for the different materials are given in Table 1 and Fig. 7.

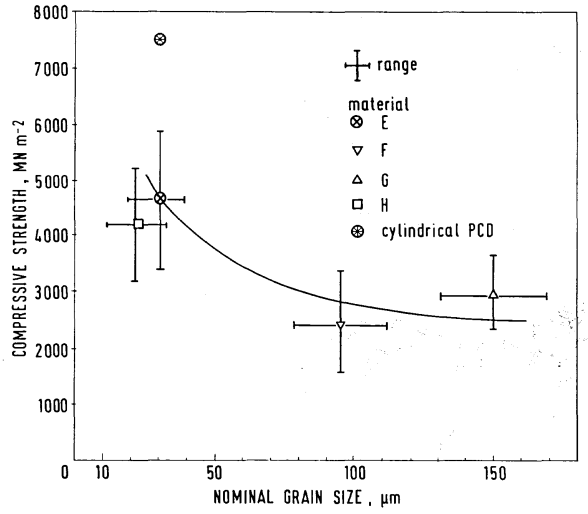
There is a dependence of K_{Ic} on grain size. This grain size dependence of fracture energy has been discussed in detail by Rice and co-workers[32,33] for various ceramics. Changes of fracture energy with grain size for cubic crystals were attributed to differences in thermal expansion between base material and secondary phase as well as to elastic anisotropy. The difference in thermal expansion between diamond and cobalt is high and this creates high interface stresses, so that microcracks might propagate in the diamond/cobalt interface. Other factors have an effect, e.g. impurities in the matrix material, the amount and size distribution of the secondary phase, and the degree of plastic deformation and fragmentation of diamond grains during synthesis.

It is still undetermined whether or not PCD is tougher than single crystal diamond. Using the Vickers indentation method, Dub[28] obtained values between 9 and 10·7 MN $m^{-3/2}$ for synthetic crystals, while Field[29] obtained 3·5 MN $m^{-3/2}$ for a natural crystal using Hertzian indentation. Values of 5–6 MN $m^{-3/2}$ obtained by Devin *et al.*[31] for PCD lie between these extremes; therefore, no real conclusions can be drawn. The fact that each set of values was obtained from a different testing technique and that no details of defect structures were given for the single crystals emphasises the general uncertainty.

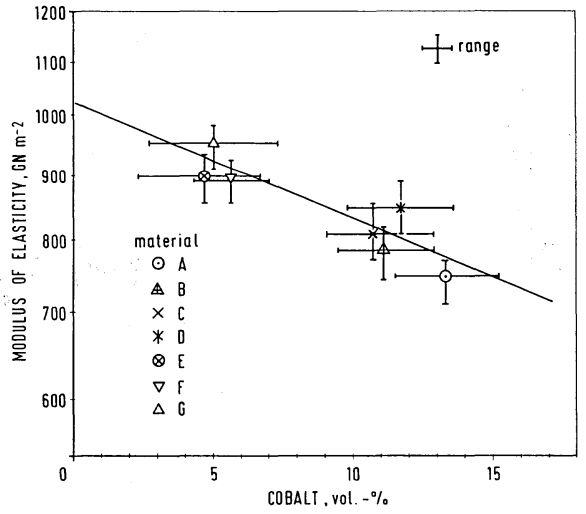
COMPRESSION TESTS

Recent work by Karihaloo[34] on the compression failure of brittle materials questioned the assumption of compressive strength as a fundamental property.

During the present investigation, it was observed that samples did not fracture catastrophically because of one crack. Multiple cracks occurred before failure which gave 'pop-ins' on the load–displacement curve with no cracks visible on the specimen surface. Because of the multiple



8 Compressive strength *v.* grain size for various materials



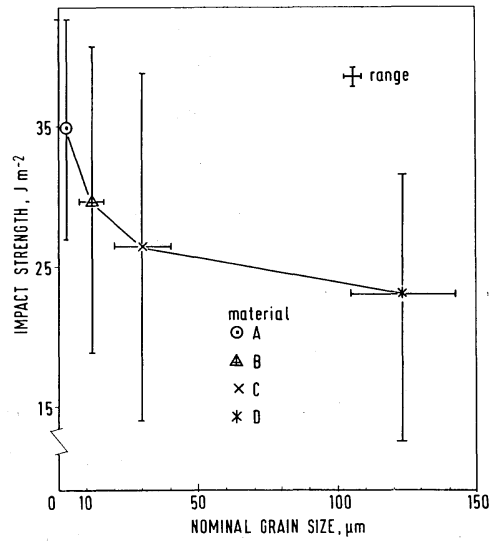
10 Modulus of elasticity *v.* volume fraction of cobalt for materials A–G

cracking, Weibull theory is not applicable and care must be taken in analysing the results because it is not possible to predict strength values for other geometries and volumes. The tests are useful only for comparing materials having identical specimen shapes. Therefore, the results reported should not be interpreted as absolute values. This was confirmed by testing a sample of material E as a cylinder of 9 mm dia. and 7 mm height in addition to standard $3 \times 3 \times 3$ mm cubes. Gigl[20] reports a value of 6900 MN m^{-2} for composites similar to material E (but gives no grain size). This is comparable to the value obtained for the cylindrical sample of material E, but much higher than that obtained using cube samples.

The present results are given in Table 1 and Fig. 8. Again, the values obtained decreased with increasing grain size for cobalt matrix materials and also silicon carbide matrix material was found to be weaker than similar materials made with cobalt.

IMPACT TESTS

Current interest in high performance drilling applications of PCD has renewed concern about its resistance to impact. To evaluate the strength of PCD subjected to high rate loading, materials A–D were tested. From the observed impact energy and the specimen dimensions, the work of fracture was calculated. The results obtained are given in Fig. 9. The scatter in observed results was fairly high, but lay in the same range as for other brittle materials such as silicon carbides.[35] Nevertheless, as for TRS, there is a tendency towards decreasing strength with increasing grain size.



9 Impact strength *v.* grain size for materials A–D

DETERMINATION OF ELASTIC CONSTANTS

The elastic constants of the materials investigated were calculated from speed of sound measurements as well as from tests carried out on a Förster Elastomat. Both methods gave the same result for material H.

The elastic constants of a solid are directly related to the speed of sound and its directional dependence in the single crystal. They can be calculated using the following relationships

$$G = \rho v_T^2 \quad \ldots \quad (5)$$

$$\mu = \frac{(v_L/v_T)^2(1/2-1)}{(v_L/v_T)^2-1} \quad \ldots \quad (6)$$

$$E = 2G(1+\mu) \quad \ldots \quad (7)$$

$$B = \frac{E}{3(1-2\mu)} \quad \ldots \quad (8)$$

where G is the shear modulus, μ is Poisson's ratio, E is Young's modulus, B is the bulk modulus, ρ is the density, v_L is the longitudinal speed of sound, and v_T is the transverse speed of sound.

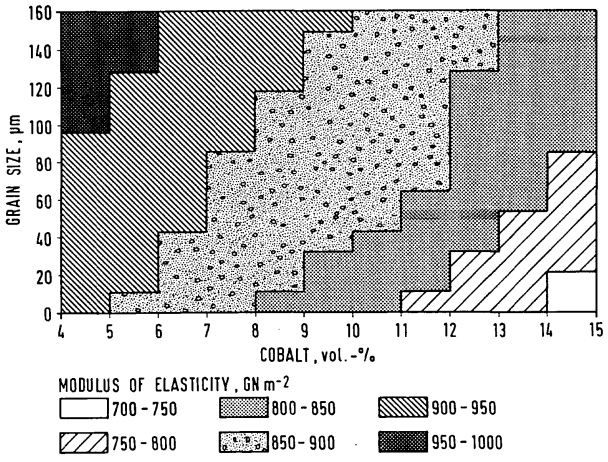
Ruoff[36] calculated the elastic constants of diamond using the method of Gubernatis and Krumhansl.[37] Dunn and Bundy[38] used values obtained by Gilmore who obtained a Poisson's ratio of 0·0781 and a Young's modulus of 1040 GN m^{-2} for PCD. These measurements were obtained by ultrasonic methods, giving no details. Dub[28] and Field[29] reported values of 0·07 for the Poisson's ratio of PCD.

The results obtained in the present work are given in Table 1. They are in good agreement with the measurements of Gigl, who obtained his values in three point bending. From the results, it can be seen that the elastic moduli depend on grain size and cobalt content (vol.-%).

Plotting the measured modulus of elasticity *v.* volume fraction of cobalt on semilogarithmic paper gives a linear relationship (Fig. 10). Therefore, the modulus of elasticity can be expressed in the form

$$E = E_0 \exp(a f_{Co}) \quad \ldots \quad (9)$$

where E_0 is the modulus of elasticity of a fully dense PCD without cobalt, f_{Co} is the cobalt content, and a is a constant



11 Modulus of elasticity as function of grain size and volume per cent cobalt for materials A–G

which depends on the shape and distribution of the secondary phase. In the present work, a value of $E = 1036$ GN m^{-2} was obtained, which is close to 1136 GN m^{-2} calculated by Ruoff.[36] This relationship between the Young's modulus of a material with pores or a secondary phase and the zero porosity material value is called the Ryshkewitch–Duckworth equation.[39] It is entirely empirical and not based on theory.

An analysis of variance revealed an influence of grain size and cobalt content on the modulus of elasticity. Therefore, the same statistical curve fitting procedure used for TRS was applied again and the results obtained are shown in Fig. 11.

It should be borne in mind that these results indicate a statistical trend based on 126 measurements by which the relationships modulus of elasticity directly proportional to grain size and inversely proportional to cobalt content are indicated for PCD.

Conclusions

1. During mechanical testing, all the PCD samples exhibited brittle behaviour and no plasticity was detected. A transgranular mode of fracture was observed using SEM.

2. Transverse rupture strength depends on grain size and cobalt content of the matrix. It increases with decreasing grain size and increasing cobalt content.

3. Fracture toughness also depends on grain size and has a maximum at the range 10–30 μm.

4. The modulus of elasticity depends on grain size and cobalt content of the PCD. It increases with increasing grain size and decreasing cobalt content.

5. The PCD having a cobalt containing matrix shows a higher strength and fracture toughness than PCD having a SiC matrix.

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