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Impact fatigue fracture of polycrystalline diamond compact (PDC) cutters and the effect of microstructure.

Kanyanta, V., Dormer, A., Murphy, N, Ivankovic, A.

1. Introduction

Polycrystalline diamond compact (PDC) cutters are widely used in oil and gas drilling [1-8]. Their superior abrasion resistance is seen as the main contributor to the greatly improved drilling efficiency and economy [1]. These cutters are composed of a layer of polycrystalline diamond bonded in-situ on to a tungsten carbide substrate as shown in Figure 1. The bonding is done during a high pressure and high temperature sintering process. The polycrystalline diamond layer is also created during this process to form a sintered material characterised by strong diamond to diamond bonding [2]. However, despite their extensive use and excellent abrasion resistance PDC tools are still highly susceptible to fractures [3-8]. This is mainly a result of their relatively low fracture toughness [9].

In oil and gas drilling, the high occurrence of impact related fractures of PDC cutters is thought to be caused by the nature of cutter loading. During drilling, cutters engage highly inhomogeneous rock formations (i.e. presence of voids and changing rock strata). Voids present in rock are likely to contain gases and/or liquids under enormous pressure, and may potentially cause significant shock waves as the cutter transition from a hard phase into these semi-porous regions. Impacts may also be caused by dynamically unstable drilling and/or drill bit whirling which can result in very high lateral forces [1, 3]. This is known to be a common occurrence when drilling through hard rock and highly inter-bedded formations. The contrasting hardness of these formations can cause severe problems with bottom-hole assembly (BHA) dynamics that result in multiple down-hole tool failures [3, 10]. Such problems include stick-slip, bit instability, and loss of drilling mud circulation.

When impact loads are above a certain threshold, cracks are initiated in the cutter and grown intermittently until catastrophic failure occurs. Once present, cracks will always tend to grow under the influence of repeated loading. Cracks may also be pre-existing from the cutter manufacturing process as internal flaws in the material, which are then grown during application. The constantly changing stress field on the cutter cutting edge due abrasive wear and pre-existing residual stresses [11, 12] also play an important role in the fracture process.

The fracture behaviour of PDC cutters under monotonic and non-impact cyclic loading has been extensively studied [3-7, 13-14]. Examples include the study by Zacny [6] who looked at the fracture of PDC cutters under both monotonic and non-impact cyclic loading. Typical fatigue behaviour was observed with the fracture load decaying by 10 to 35% after cyclic loading. In another study by Moseley et al. [4], the wear and fracture mechanisms of PDC cutters was studied using core drilling in reinforced concrete. Gross fracturing of relatively un-worn cutters was found as the predominant failure mechanism. Dunn and Lee [14] performed fatigue tests on sintered PDC and, like Moseley et al. [4] and Zacny [6], also reported a reduction in fracture stress due to repeated loading. In addition, Dunn and Lee suggested that fatigue in PDC was likely to be caused by some irreversible processes involving opening and closing of sub-critical cracks followed by the gradual growth of the same

[14]. However, most of these studies have only looked at non-impact cyclic loading. The only exception would be in the case of core drilling of reinforced concrete where significant impact loads can be induced as the tool engages and exits the imbedded steel bars. Therefore, they may be inadequate to predict cutter behaviour under repeated impact loading. This is because the mechanical and fracture properties of polycrystalline diamond have been shown to vary considerably with loading rate [9]. It can also be argued that repeated or cyclic impact loading is more closely representative of the in-service cutter loading (especially during dynamically unstable drilling) than is non-impact cyclic loading [3-5].

In the current study cutters were subjected to repeated impact loads using an in-house built cyclic impact testing (CIT) machine. Impact speeds were chosen to be as representative of in-service cutting speeds as possible, which under normal loading are assumed to be in the range of 1-5 m/s [10]. These speeds are estimated from the drill bit's diameter and rotation speeds during drilling. The applied impact force was varied in order to generate full stress vs. number of loading cycles (S-N) fatigue curves.

2. Materials and Methods

2.1 Materials

The PDC cutters tested have a diameter of 13.4 mm and a diamond layer to tungsten carbide thickness ratio of approximately 0.25. Two cutter variants, i.e. PCD-A and PCD-B, were tested. The difference between the two variants is the polycrystalline diamond layers which have different microstructures and composition. The layer for PDC-A has a fine grain microstructure while that for PDC-B has a coarse grain microstructure as shown in Figure 2. The average grain sizes are 6 μm and 30 μm for PCD-A and PCD-B, respectively.

2.2 Experimental Tests (Cyclic Impact)

Cutters were tested in cyclic impact loading on an in-house built cyclic impact testing (CIT) machine, with the set-up as shown in Figure 3. The anvil impacts the cutter off-centre so that only a portion of the cutter is loaded. This offset, w, (Figure 4) was fixed at 2mm. If w is too larger, much higher forces would be required to cause fracture and if very small failure would occur at very low loads. The value used here suits the range of impacts loads generated on the CIT. The diameter of the impact plate was 19.5 mm. These plates are made of tungsten carbide with an average grain size of 2 μm and 10wt% cobalt. During testing, a cutter is secured in a cutter holder by means of an interference fit.

Three stages of cutter failure were identified, i.e. first visible surface crack (FVSC), crack growth through the polycrystalline diamond layer (CG-PCD) and catastrophic failure (CF). Here catastrophic failure is defined as extensive cracking and large-scale chipping or gloss fracturing. During application, a cutter will continue cutting until catastrophic failure occurs. The first two criterions (i.e. FVSC and CG-PCD) are relatively more difficult to quantify as they are based on visual inspection of the cutter. As a consequence, the test was stopped at set intervals and the cutter surface inspected for surface cracks and the extent of crack growth in the polycrystalline diamond layer. FVSC is the first appearance of a visible crack at the top surface of the cutter and CG-PCD is when the crack extends to more than 2mm into the polycrystalline diamond layer thickness. Figure 5 shows examples of the three failure criterions used, i.e. FVSC (Figure 5(a)), CG-PCD (Figure 5(b) and CF (Figure 5(c)).

The applied cyclic impact force/energy amplitude was varied in order to obtain fatigue curves for the two materials. At each impact force the number of impacts to FVSC, CG-PCD and CF is recorded. The impact speed for all the tests was kept fixed at 2±0.02 m/s and the cyclic impact frequency fixed at 2 Hz. Five to six cutters were tested for each data point in order to get some measure of repeatability of the results. All the tests were performed under room temperature conditions. However, high temperature testing is also feasible but was beyond the scope of the current study. Impact force is varied by either increasing the carriage mass or by simply increasing the applied air pressure during the downward stroke (Figure 3). Increasing the later also increases the impact speed, which makes it possible to achieve test speeds much higher than free-fall speeds. The test set-up is equipped with an auto-stop mechanism for stopping the test after a pre-set number of impacts are reached. Typically cutters were examined for cracks or damage at intervals of 10 impacts for the first 500 impacts, then 50 impacts up to 2000 impacts and thereafter at intervals of 100 impacts. Tests were stopped when catastrophic failure occurred or after 5,000 impacts are reached. Figure 6 shows the typical force trace recorded by the force transducer. The duration of each pulse is about 1ms and the frequency of impacts = 2 Hz.

3. Results

The test results for the two PDC cutter variants are presented in Figure 7(a) and 7(b) in form of force (or stress) vs. number of impacts to failure (S-N curves) for PDC-A and PDC-B, respectively. Three curves are plotted in each case, showing the number of impacts to first visible surface crack (FVSC), crack growth through polycrystalline diamond layer (CG-PCD) and catastrophic failure (CF) at each force amplitude. The results show a typical fatigue behaviour pattern with the force or stress needed to cause fracture decreasing with the number of cycles. As the applied force continues to be lowered, it approaches an asymptote, also known as a fatigue threshold. This threshold, obtained by fitting an exponential curve to experimental data, is estimated to be around 28.5 kN (2.75 GPa) and 31.5 kN (3.04 GPa) for PDC-A and PDC-B, respectively. The three curves (FVSC, CG-PDC and CF) when extrapolated backwards converge at a single point on the vertical axis, which corresponds to the single impact to failure. This is about 54 kN for PDC-A and 58 kN for PDC-B. At this force (or impact energy) there is sufficient energy to initiate cracks and almost instantaneously grow them to catastrophic failure in a single impact. Hence the three events (crack initiation, growth and catastrophic failure) appear superimposed in one single event. This is normally the value that would be measured in the traditional impact drop tests. At any force amplitude less than this critical force, an initiated crack tends to extend with each successive impact until it reaches a critical size to cause catastrophic failure. This is believed to also be the case during application where cutter failure is likely to result from multiple impact loads. The significance of these curves is that if the average impact force amplitude associated with a given application is known, the number of cycles to FVSC until catastrophic failure can easily be estimated.

The high scatter in the results, especially for CF, is expected for the fatigue fracture of such brittle materials. This can be due to the non-uniform distribution of pre-exiting flaws in the bulk of the material. The number and distribution of these flaws is also expected to vary between the cutters. As a consequence, the variation in the number of impacts to failure is high. In addition, fatigue is a stochastic process and often shows considerable scatter even in well controlled experiments. This scatter tends to increase for longer fatigue lives. Therefore, the scatter is less for FVSC and CG-PCD in comparison to CF as also shown in Figure 7. Figure 8(a) shows the schematic of the sample loading configuration. The first sign of cutter failure during the test was the formation of circular cracks on the top surface of the polycrystalline diamond layer of the PDC cutter. This occurs just outside the impact contact region as shown in Figure 8(b). Once initiated the cracks continue to grow with each successive impact until catastrophic failure occurs (Figure 8(c).

Sub-surface crack growth was also studied by sectioning cutters after a given number of impacts (before catastrophic failure occurred) using electron discharge machining (EDM). Following this, samples were polished and then studied under a scanning electron microscopy (SEM). Figure 9 shows an example of the sectioned cutter, sectioned along X-X (Figure 9(a)). The image of the sectioned and polished sample is shown in Figure 9(b). The geometry of the crack, i.e. location of crack initiation and the angle it makes with the surface (Figure 9(b)), is very consistent with Hertzian fatigue crack in brittle ceramics under contact loading (Figure 10) [15-18]. Figure 10(a) show the schematic of the contours of maximum principal stresses and the likely location of cracks as them form and propagate into the bulk of the material [15]. This is assuming a semi-infinite elastic medium in contact with a spherical indenter, with the area of contact represented by the distance AA. An example of Hertzian contact crack in a brittle material, i.e. Silicon Nitride, is also shown in Figure 10(b).

Typical values of the angle the crack makes with the surface has been reported to be 20-30^o for pure mode I [15-18] and 30-55^o for mixed mode I/II crack propagation [17]. In the current study, this angle is about 47^o (Figure 9(b)). However, this may not necessarily suggest mixed mode of crack propagation. It may be due to the presence of high pre-existing residual stresses in the PDC cutter [12]. Fracture in this case can still be predominantly under mode I, with the crack following the normal stress or maximum principal stress trajectories. Figure 9(b) also shows abrupt change in the direction of the main crack as it approaches the interface between the polycrystalline diamond layer and the carbide substrate. This can be attributed to the influence of the high tensile residual stresses in this region [11, 12]. The crack bifurcates into two cracks with the small crack continuing in the same direction of the initial crack as shown in Figure 11. The larger crack is pulled towards the polycrystalline diamond-substrate interface and into the substrate. The other possible reason for the change in crack direction and/or crack bifurcation is the influence of the applied supporting pressure, p (Figure 8(a)).

At any given force amplitude (e.g. 43.5kN), one can also compare the performance of the two cutter variants in terms of number of cycles to failure as shown in Figure 8. PDC-B exhibit far superior impact resistance compared to PDC-A. It takes an average of 280 impacts for the first visible crack to appear on the cutter top surface for PDC-B compared to 120 impacts for PDC-A. Also for catastrophic failure, about 3200 impacts are needed for PDC-B compared to only 1700 impacts for PDC-A under identical loading conditions (i.e. impact force of 43.5 kN). Overall the PDC-B cutters, which have a polycrystalline diamond layer with a coarser grain microstructure, exhibits up to 70% better impact fracture resistance than their fine grain counterparts (i.e. PDC-A).

2 Discussion

Impact loads, induced stress waves (shocks) due to sudden changes in rock strata, high temperature and pressure at the cutting tip and pre-existing residual stresses in the cutter are some of the factors leading to the fracture of PDC cutters during oil and gas drilling. Cracks in the cutters are initiated and grown when the combination of these factors favours crack growth. In the current study, the effect of cyclic or repeated loading on the fracture and fatigue behaviour of the cutters was investigated. Cutters were subjected to controlled cyclic impact loading until failure or up to 5,000 impacts for each given force amplitude. The results show typical fatigue behaviour with the fracture stress decreasing as the number of loading cycles increase. For the two grades of PDC cutters tested, results show that PDC-B, which is a coarser grain material, has better fracture resistance under cyclic impact loading than PDC-A. The fatigue threshold for PDC-A, approximated by conservatively projecting the curves forward, is at least 10% lower than that of PDC-B. The differences in behaviour are even a lot clearer when one looks at the number of impacts to failure at fixed cyclic load amplitude as shown in Figure 8. PDC-B sustains almost double as many impacts before failure occurs compared to PDC-A. Therefore, under impact related applications such as rock drilling, PDC-B would offer better performance compared to PDC-A.

The error bars on the results show very high scatter for catastrophic failure compared to the other two failure criterions, i.e. FVSC and CG-PCD. This is expected as this failure type is controlled by multiple cracks and their coalescence and, thus, is a very random process. For FVSC and CG-PDC, the error bars are smaller indicating good repeatability. Here, the fracture process is predominantly controlled by a single running crack. The differences in fatigue curves for FVSC and CG-PDC can also be used to be indicative of the material's crack growth resistance. This is in the absence of crack growth measurements which is extremely difficult to do for test specimens such as the ones used in the current study (i.e. cylindrical cutters), not mentioning the high complexity of performing such measurements on very brittle materials (i.e. polycrystalline diamond).

Although more impacts that 5,000 would be desired for fatigue testing, it was considered to be unnecessary and time consuming. This is because It was possible to quantify fatigue crack growth behaviour in a PDC cutter with 5,000 impacts. Initial tests were done up to 100,000 impacts but this did not add any significant value to the results seen at 5,000 impacts. If cracks did not appear after 5,000 impacts, they were unlikely to form even after 100,000 impacts without having to increase the applied impact force. It should also be mentioned that the fatigue threshold for these ultra-hard and brittle materials is in some cases very close to the fracture stress under monotonic loading. This leaves a very small window for evaluating fatigue behaviour. In addition, as seen from the results, fatigue curves are also very steep and levels off quite quickly (i.e. low cycle fatigue). Therefore, limiting the number of impacts to 5,000 can be considered reasonable.

It should also be noted the current study assumes a constant amplitude cyclic load for each individual experiment. In the actual drilling application, however, cutters are likely to be subjected to non-constant amplitude cyclic loads. This makes any analysis of life predictions extremely challenging and the only way such predictions can be made is by ignoring low-amplitude loads which are below the fatigue threshold and assuming some average impact load. Low amplitude loads can be ignored since failure would not occur as long as the applied load is below the fatigue endurance limit.

Assuming some average cyclic impact load would significantly simplify the analysis since fatigue failure and life predication under constant amplitude cyclic loads has been extensively studied for brittle materials [17-20]. Some of the examples include the work of Maity and Sarkar [19] who studied the impact fatigue of a porcelain ceramic. Their results showed typical fatigue behaviour with increasing endurance at decreasing impact energy levels. Other studies include the work of Bhowmick et al. [20] who looked at the fatigue failure of glass, alumina and zirconia under concentrated cyclic loading. In another study, Bhowmick et al. [17] studied the nature of fatigue and debris generation in bulk Silicon. The fatigue analysis employed in these studies can also be applied to PDC cutters using experimental tests such as the one presented in this study.

3 Conclusion

PDC cutters exhibit typical fatigue fracture behaviour when subjected to repeated impact loads. The fracture stress decreases with increasing number of loading cycles. Cracks are seen to be initiated and grown intermittently with each successive impact until failure. Cutters with a polycrystalline diamond layer having a coarse grain microstructure offer a lot more impact resistance compared to their fine grain counterparts. PDC-B cutters showed an impact fatigue crack growth resistance of up to 70% better than PDC-A cutters. The fatigue endurance limit is also about 10-15% higher than that of PDC-A cutters. Therefore, PDC cutters with a polycrystalline diamond layer having a coarse grain microstructure are likely to perform better in applications where impact loading is the primary consideration.

Acknowledgments

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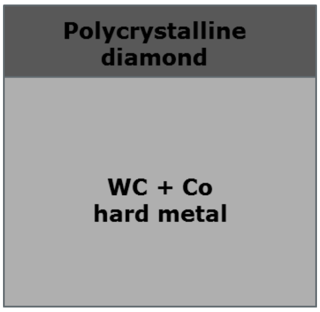


Figure 1: Geometry of a typical PDC cutting tool used in Oil & Gas drilling.

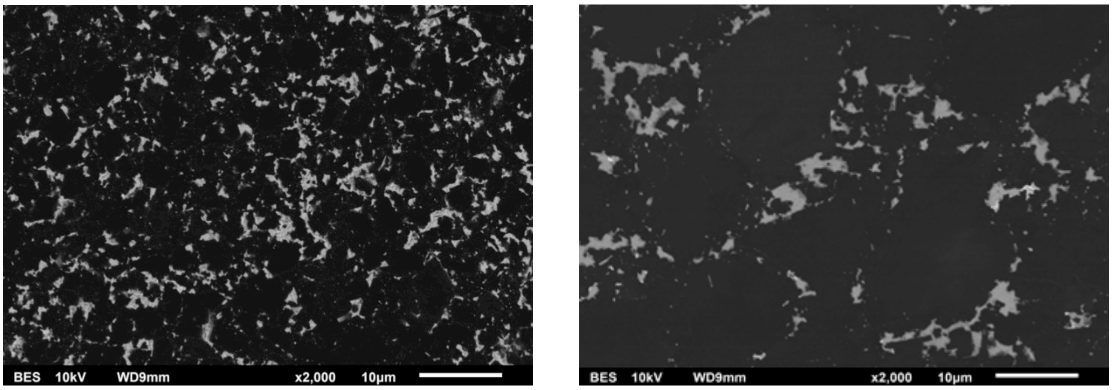
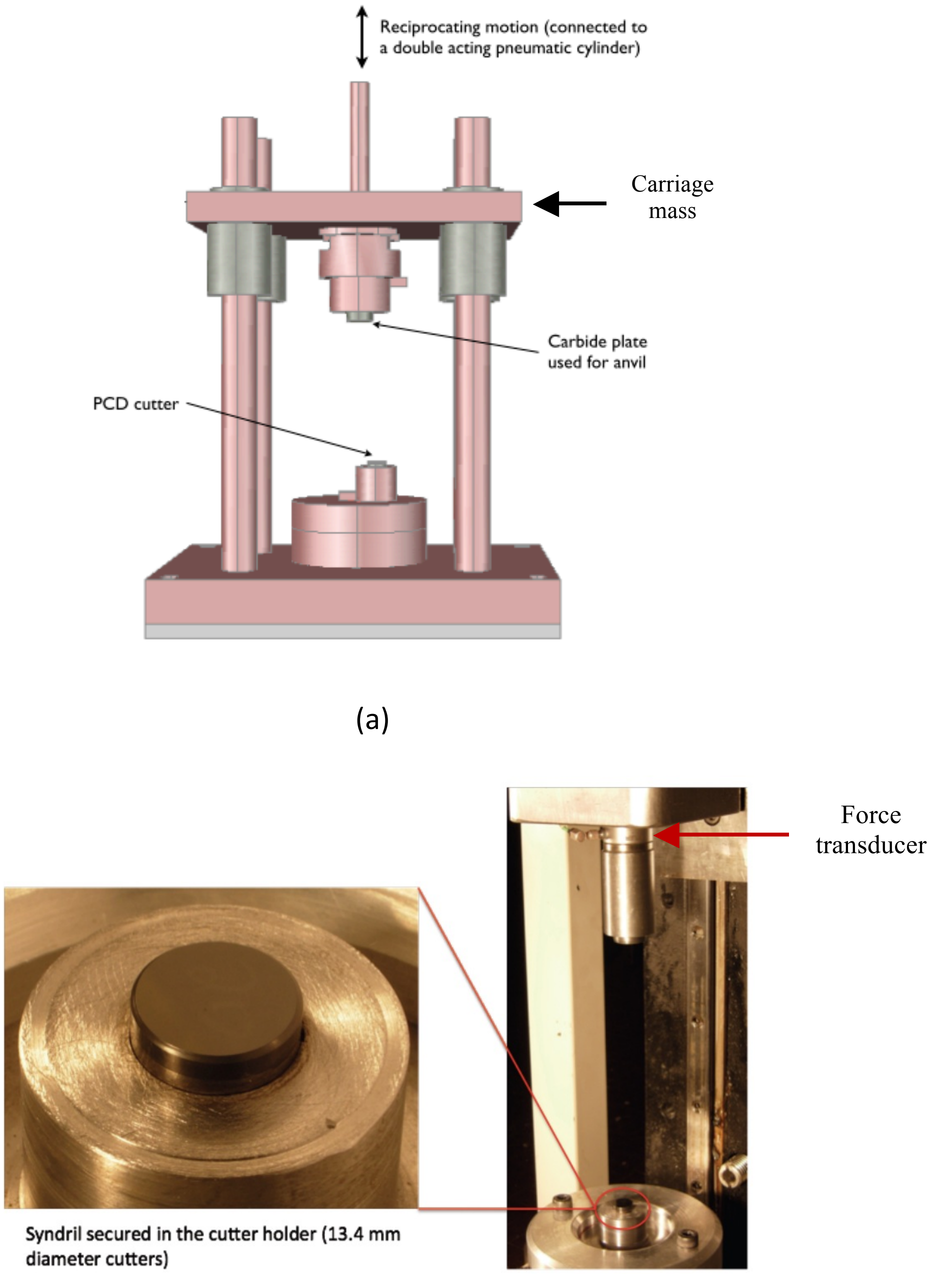


Figure 2: Representative microstructures of the polycrystalline diamond layer for PCD-A (left) and PCD-B (right). Average diamond grain sizes are 6 micrometres and 30 micrometres for PCD-A and PCD-B, respectively.



(a)

(b)

Figure 3: (a) Schematic of the in-house built cyclic impact testing (CIT) machine and (b) close-up view of the test set-up showing the PDC cutter secured in a cutter holder and the transducer for force measurements.

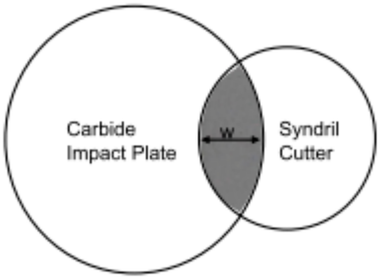


Figure 4: Schematic of the anvil (carbide impact plate) and cutter contact geometry on impact. The offset, w, is fixed at 2mm for the current study.

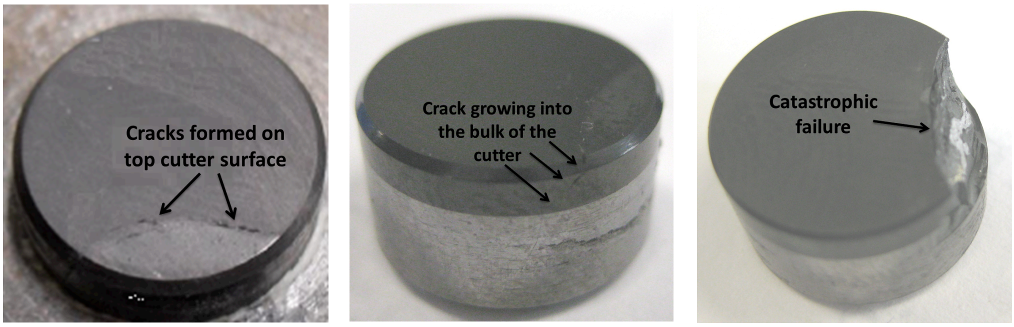


Figure 5: Failure of the PDC cutter under cyclic impact loading, showing the (a) initial stage, (b) intermediate stage where the crack has extended by more than 2mm into the diamond layer thickness and (c) final stage (catastrophic failure).

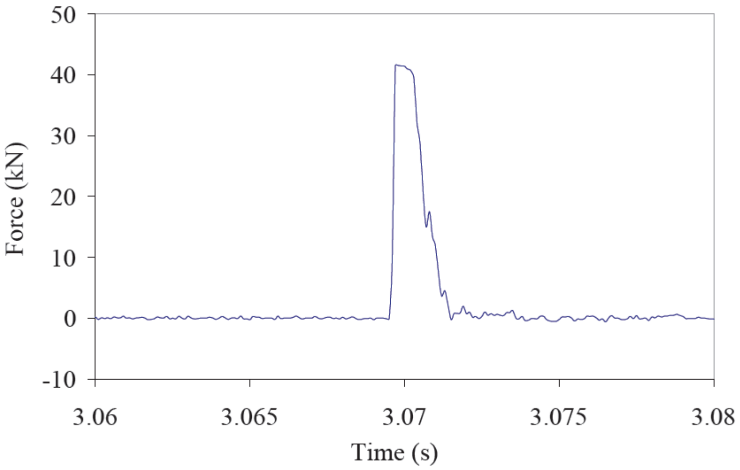
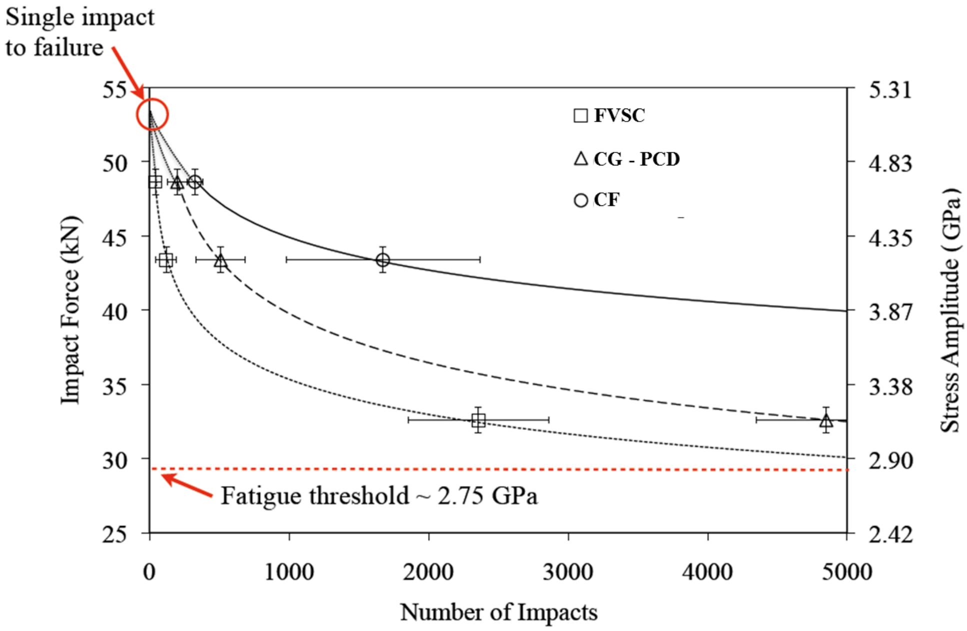
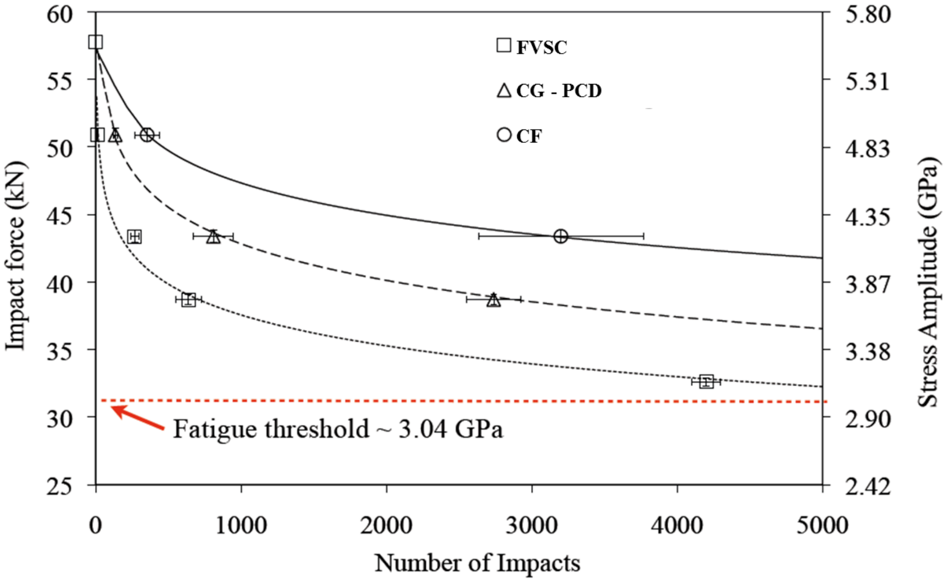


Figure 6: (a) Applied cyclic impact force (recorded by force transducer) and (b) blow-up of the force pulse.



(a)



(b)

Figure 7: Cyclic impact S-N fatigue curves for (a) PDC-A and (b) PDC-B. Three curves plotted in each case, i.e. first visible surface crack (FVSC), crack growth through PDC thickness (CG-PDC) and catastrophic failure (CF).

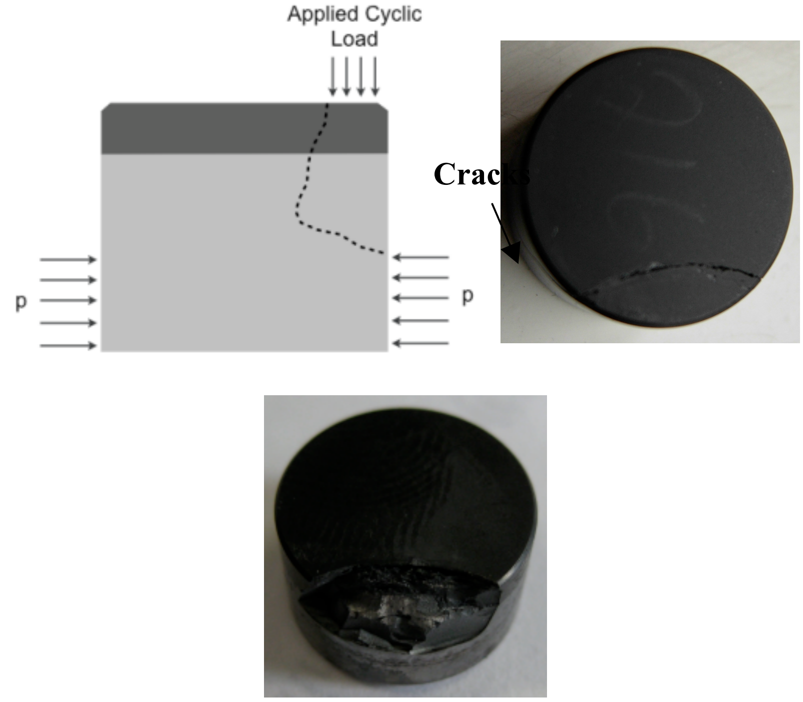
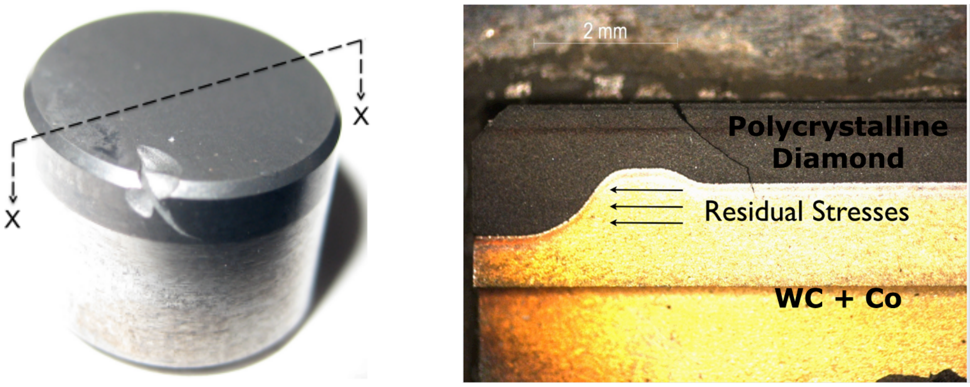
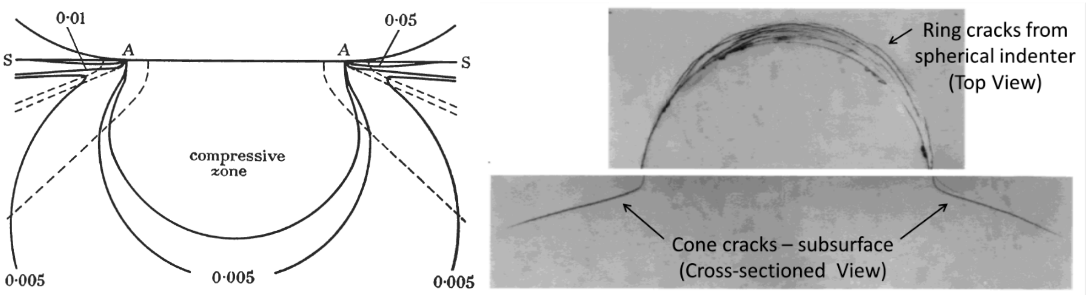


Figure 8: Schematic of the observed crack growth pattern in PDC cutters (left), image of the cutter showing circular crack on top surface (middle) and catastrophically failed cutter (right).



(a) (b)

Figure 9: (a) Tested cutter (before catastrophic failure) EDM cut along X-X, and (b) polished cross-section after sectioning (EDM cutting) showing crack growth pattern.



(a) (b)

Figure 10: (a) Contours of maximum principal stress in a semi-infinite elastic medium (reproduced from the work of Frank FC and Lawn BR [15]), and (b) Hertzian contact damage in F-Si_3N_4 (reproduced from the work of Seung Kun Lee et al. [16])

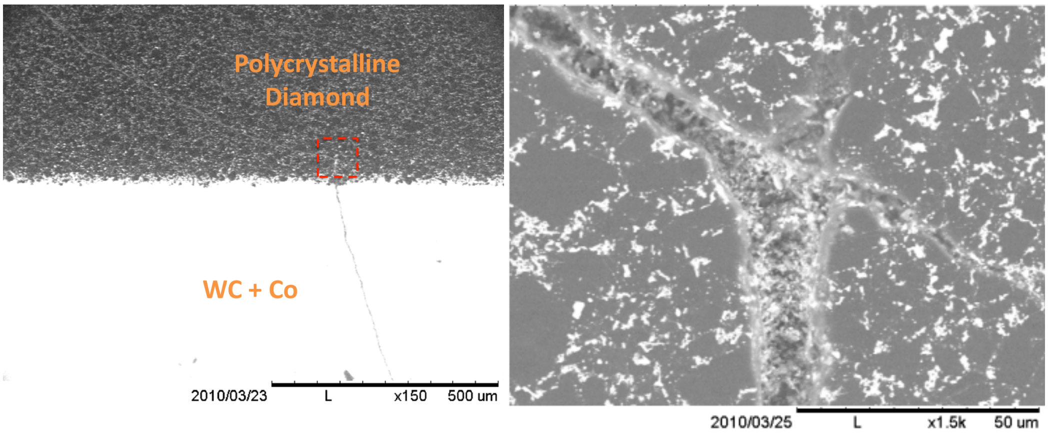


Figure 11: SEM images showing change in crack direction (and bifurcation) at the PDC-substrate interface. Right: close-up of the image on left, showing attempted crack bifurcation on path change.

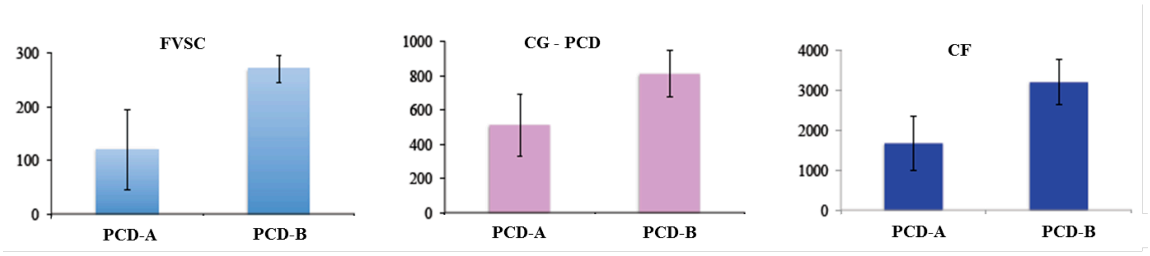


Figure 12: Comparison of cutter performance in terms of number of impacts to FVSC, CG-PCD and CF at a fixed cyclic force amplitude of 43.5kN.