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POLYCRYSTALLINE DIAMOND COMPACT (PDC) DESIGN METHODOLOGY UTILIZING STRAIN ENERGY CAPACITY

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ABSTRACT

Polycrystalline diamond compact (PDC) bits have gained wide commercial acceptance in oil and gas drilling due to their high rates of penetration, long life and mechanical simplicity. However, PDC bits have had limited success at drilling high compressive strength and abrasive rock formations. One of the limitations to hard rock drilling is the propensity of the cutters to fracture. This paper examines the use of strain energy capacity as an index of fracture resistance under dynamic and static loading. The cutter and the bit absorb energy during a down-hole impact event. This absorbed impact energy is converted to strain energy as the cutter deforms under the applied load. Cutters with higher strain energy capacity will be able to absorb more impact energy during drilling without exceeding the diamond tensile limit. PDC cutters with various diamond/carbide interface geometries and diamond thickness were modeled with finite element analysis (FEA). The FEA models included both residual stress loads and simulated impact loads. Strain energy capacity was calculated after adjusting the impact load to produce a critical tensile stress on the diamond surface. Laboratory drop-tower impact testing was done on each of the calculated designs. Designs were then ranked based on calculated strain energy capacity and experimental drop tower results. Agreement, though not perfect, is promising. These tools hold the potential to quickly screen cutter designs before undertaking the risk of testing a bit down-hole. They also allow the incorporation of residual and brazing stresses, which can be significant.

INTRODUCTION

Since their introduction over 20 years ago, polycrystalline diamond compact (PDC) cutters have made a significant impact on the oil and gas drilling industry [1]. Bits equipped with PDC cutters now account for a significant portion of the total footage drilled [2]. High rates of penetration, long life, and simplicity are some of the benefits afforded by PDC bits. However, PDC bits have had limited success at drilling high compressive strength and abrasive rock formations. One of the limitations to hard rock drilling is the propensity of the cutters to fracture. Fracture toughness of PDC cutters is especially important in the presence of bit whirl [3].

New PDC cutter designs must be evaluated for fracture toughness prior to field application. Correctly simulating the impact that drilling imparts to a cutter has been the subject of extensive research, and several different approaches have been used [4,5]. Some are strictly impact experiments where a dynamic blow is imparted to the cutter with a target or strike plate. Others could be more accurately characterized as dynamic rock cutting experiments.

This paper proposes a novel procedure for evaluating cutter toughness. First PDC cutters with various diamond/carbide interface geometries and diamond thickness were modeled with finite element analysis (FEA). The FEA models included both residual stress loads and simulated impact loads. Strain energy capacity was calculated after adjusting the impact load to produce a critical tensile stress on the diamond surface. The strain energy is used as an index of fracture resistance under dynamic and static loading. PDC cutters with high strain energy capacity should have increased fracture resistance.

To validate the model results, laboratory drop-tower impact testing was done on each of the calculated designs. A correlation was then established between calculated strain energy capacity and experimental drop tower results. A correlation between static strength and drop-tower results was also investigated. An explanation of the laboratory drop-impact test is presented as well.

NUMERICAL MODELING PROCEDURE

An energy approach can be effective in evaluating dynamic loads for many problems in mechanics. During a laboratory impact test, energy is transferred from the test equipment to the PDC cutter. In a down-hole situation, energy is transferred from the bit and PDC cutters to the formation. Deformation of the cutter under a dynamic load will depend on the usual mechanics parameters as well as the strain wave velocity. The effect of strain wave propagation has been neglected for this analysis due to the high speed of sound in PDC (approximately 10 km/s) [6]. This assumption may not be valid for all load cases experienced by PDC. With this assumption, the dynamic load can be approximated by an equivalent static load that produces the same maximum deflection. The work done by the equivalent static load in deforming the cutter is equivalent to the strain energy stored in the cutter.

Designs with high strain energy capacity can absorb more impact energy before failure. As an example, consider two cantilever beams, one straight and one tapered, with the same length and root dimensions. Equal forces applied to the end of each beam will create equal maximum tensile stresses at the root. Thus each beam has equivalent static strength. However, most of the straight beam's volume is unstressed, leading to inefficient energy storage. In contrast, most of the tapered beam is stressed, allowing more strain energy to be stored. Equal kinetic energy applied to each beam would result in equal amount of strain energy stored. Yet the tapered beam would have lower peak stresses. In other words, the tapered beam can absorb more kinetic energy and convert it to strain energy before reaching the same peak tensile stress as the straight beam. Thus the tapered beam has higher dynamic strength than the straight beam. This same principle can be used to evaluate PDC designs.

Computing the strain energy index is performed using a finite-element model. We begin by modeling residual stress. Residual stress is inherent to the PDC manufacturing process and may be of the same magnitude as the diamond tensile strength. A laboratory drop-impact event is then simulated in the model with an applied static load. Residual stresses are superimposed upon the applied static load stresses. The static load is adjusted until the maximum combined tensile stress reaches a pre-determined level on the diamond surface. The finite element model is then used to compute the total strain energy stored in the cutter under the combined loads.

A commercially available FEA package was used for this study. The software assumes linear static behavior of the materials and perfect attachment of the diamond layer to the carbide substrate. A fully adaptive p-version of the finite element method is used to converge on the solution [7]. The material properties used for this analysis are listed in Table 1.

Table 1. Material properties used in the FEA models [6,8].

	Tungsten Carbide	Polycrystalline Diamond
Elastic Modulus (GPa)	545	850
Poisson's Ratio	0.22	0.22
Thermal Expansion (K^{-1})	5.9×10^{-6}	2.4×10^{-6}

Only a quarter section of each PDC was modeled to save computational space. An axisymmetric boundary condition was applied to the inner faces of the quarter section. The displacement of the back of the cutter was fixed to simulate the drop-impact test fixture support. Fixing the displacement of the cutter base is more restrictive than a free thermal expansion boundary condition necessary for residual stress computation. However, most of the residual stress displacement occurs near the diamond/carbide interface and is sufficiently removed from the back of the cutter to have virtually no effect [9]. Analysis shows the residual stress error to be less than 1%.

Residual Stress Model:

PDC is sintered under conditions where diamond is the thermodynamically stable phase of carbon and where metal solvent/catalysts enhance the diamond-to-diamond bonding kinetics (1500–2000 °C and 50–70 kbar) [10]. The individual diamond crystals bond together and to the tungsten carbide substrate under these extreme pressure and temperature conditions. The diamond layer and substrate material respond at different rates as pressure is released and the PDC cools, giving rise to significant residual stresses.

A simple change in temperature can be used to model the combination of both pressure and temperature changes after sintering. A good match between experimental measurements and numerical calculations of residual stress occurs when a temperature change of –380 ºC is applied to all elements of the model [11].

A three-dimensional residual stress model of a quarter section of a flat interface PDC is shown in Fig. 1. This cutter is 13mm in diameter, 13mm in length, and has a 1-mm thick diamond table. Fig. 1 shows the maximum tensile stress (first principal stress) in the cutter. The substrate material wants to contract about twice as much as the diamond layer for a given temperature change. This generally puts the carbide into tension (red) and the diamond into compression (blue). The exception occurs near the outer diameter of the cutter. Here the cutter begins to bend and the diamond is no longer simply compressed. The regions of high residual tensile stress around the diamond outer diameter and on the diamond surface weaken the cutter. The high tensile stress regions can lead to delamination and spalling of the diamond table, especially for thick diamond PDC with a planar interface.

Strain Energy Model:

The strain energy model simulates the laboratory drop-impact test used to evaluate PDC toughness. A parabolic pressure load was applied to a region of the cutter face and side roughly equivalent to the strike-plate indentation area after a 60 J impact. The loaded region consists of the area cut out by a plane oriented at 15 degrees relative to the side and 2.5mm back from the cutting edge. The FEA model superimposes the residual stress distribution with stresses from the static load. The applied load is modified until the maximum tensile stress on the diamond surface equaled 550 MPa. This is near the tensile limit of the diamond in PDC and experimental observations of PDC fracturing [6,11].

The magnitude of the applied load that creates the peak 550 MPa stress is the static strength of the cutter. The static strength will depend both on the stiffness of the cutter geometry and the residual stress state of the diamond surface. A three dimensional FEA model result including both residual stress and the applied static load is shown in Fig. 2. This is a plot of the maximum tensile stress in the model. The peak tensile stresses on the diamond surface generally occur on the diamond face near the edge of the applied static load.

The magnitude of the strain energy stored in the model is a measure of the dynamic strength. A plot of the strain energy distribution is shown in Fig. 3. The diamond table is very stiff and does not deflect much under the applied load. Thus the strain energy contained in the diamond table is small. The substrate is more compliant and thus able to store more energy. The strain energy capacity of a cutter (dynamic strength) will depend on the material properties, geometry, and residual stress state.

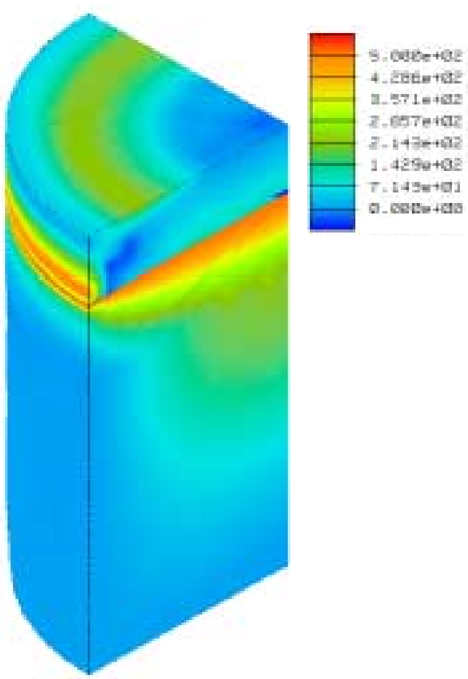

Fig. 1. Maximum residual tensile stresses in a flat-interface 1313 PDC cutter.

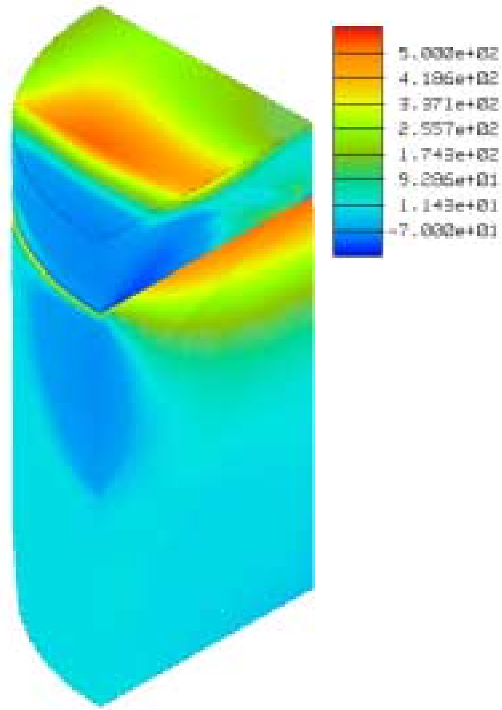

Fig. 2. Maximum tensile stress due to the simulated drop-impact load combined with residual stress from Fig. 1.

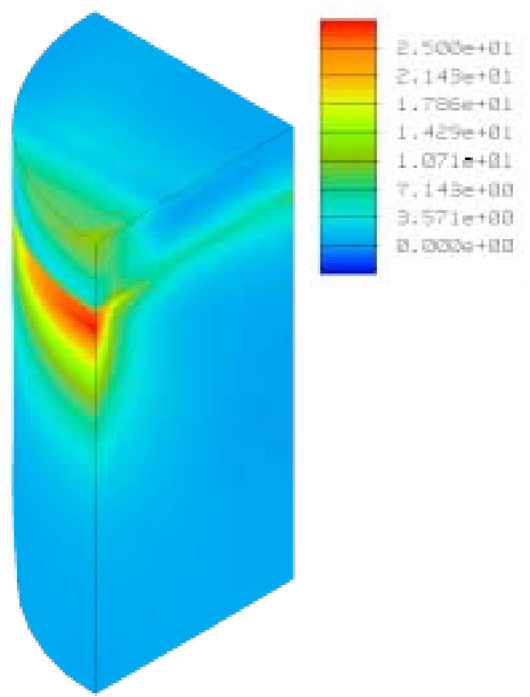

Fig 3. Strain energy distribution in a flat interface 1313 PDC cutter.

DROP-IMPACT TESTING

We have implemented and developed an impact test protocol in which a calibrated blow is dealt the cutter on the cutting edge with a weight that has been dropped from a controlled height. A strike plate of consistent hardness is placed between the cutter and the weight. During the impact this plate plastically deforms providing a controlled deceleration of the weight and thus a consistent impulse loading. The cutter is positioned at a 15 degree back rake and the blow is in the direction of what would be the direction of advancement were the cutter on a bit (see Fig. 4). This orientation provides a simulation of a weight on bit directed blow for a typical bit nose cutter. This is also a vulnerable orientation for the cutter's heavily stressed diamond / tungsten carbide (WC) interface.

Each cutter tested is subjected to several blows, usually ten, with the weight dropped from a constant height and the strike plate repositioned such that each blow will be on a fresh (not dented) surface. The cutter is also inspected and the extent of damage and type of fracturing recorded. The testing is terminated if over 30% of the cutter face area is removed or the cutter catastrophically fractures before the ten loadings. This procedure is then repeated on a new cutter at a new drop height. A full suite of tests usually consists of testing at least 20 cutters at drop heights corresponding to potential energies of 20, 40, 60, 80, and 100 joules (4 cutters per energy level). A test suite represents 200 individual drops if each cutter were to go the full ten loadings before failure.

A drop tower shown in Fig. 5 is used to perform these tests. It consists of a 20 kg drop weight that is positioned within 0.5 mm height using a closed-loop motion control system. When the weight reaches the correct position it is dropped via a magnetic release. Fixturing holds the cutter in a tight tolerance holder (0.008 to 0.018 mm diametrical clearance) made from D2 tool steel heat treated to at least 58 HRC. Currently the entire machine is rigidly mounted to the shop floor. Decelerations have been measured and found to be approximately 700 g's for a 100 J drop and correspondingly less for lower energies as shown in Fig. 6. A typical loading pulse for 100 joules is shown in Fig. 7 and is approximately 1 millisecond in duration.

Drop test results are viewed on a plot of percent cutter spall versus drop energy as shown in Fig. 8. Percent cutter spall is the percentage of cutter face area that is removed. Percent spall numbers above 30% are considered failure independent of the fracture type. Each data point represents the end point of a ten-drop sequence for a particular cutter. If failure occurs, a number is written next to the data point indicating the number of drops experienced before failure. A code accompanying the number indicates the failure type (MF in Fig. 8 indicates "massive fracture"). On the top margin is a histogram representing the distribution of cutters tested at each energy level, and on the right vertical margin is a the distribution of cutter face area lost. The mean value of this distribution is calculated and used as the comparison metric for impact strength reported in this paper.

In our data two main failure modes are observed. The first is a general chipping or spalling. Almost every cutter tested spalls at the 1 to 2% level on the first or second hit, then progresses from there to as high as 100% spall. It is important to note that in the tests reported here the weight is allowed to rebound after each individual blow and strike the cutter a second, third…time. The rebound related cutter loading occurs at the same position on the already dented (from the first blow) strike plate. This repeated loading on an already deformed strike plate has been shown to be primarily responsible for the general spall failure mode. Fig. 9 shows a typical example of cutter face damage that corresponds to this failure mechanism. The second failure mode is total fracture. This occurs randomly, and Fig. 10 shows a typical example. The impact test metric, which is the mean of the total cutter spall distribution, includes both of these failure types.

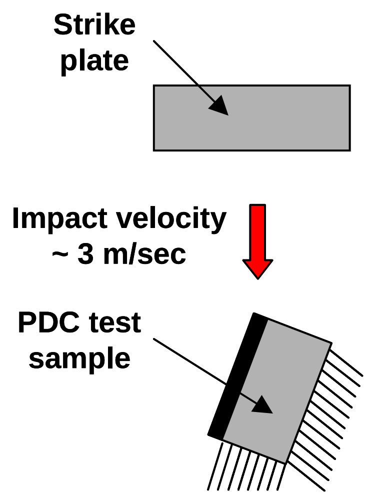

Fig. 4. Schematic of drop-impact test blow.

Fig. 5. Drop tower apparatus.

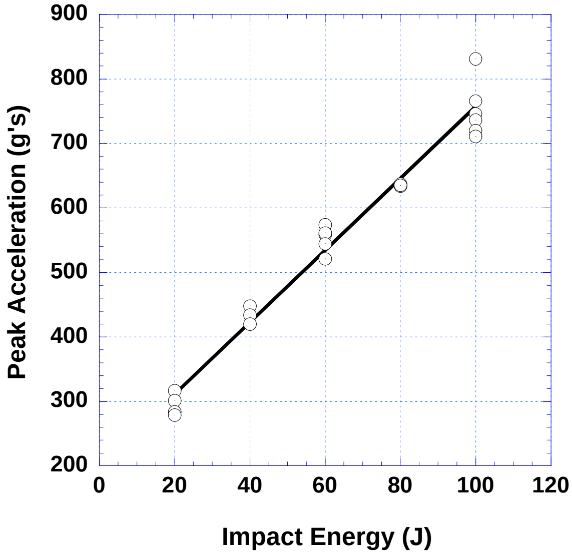

Fig. 6. Measured drop-tower acceleration as a function of impact energy level.

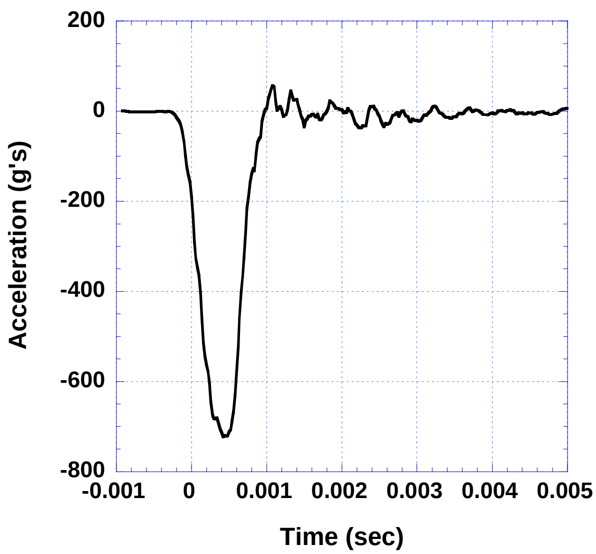

Fig 7. Accelerometer response during a 100 J impact event.

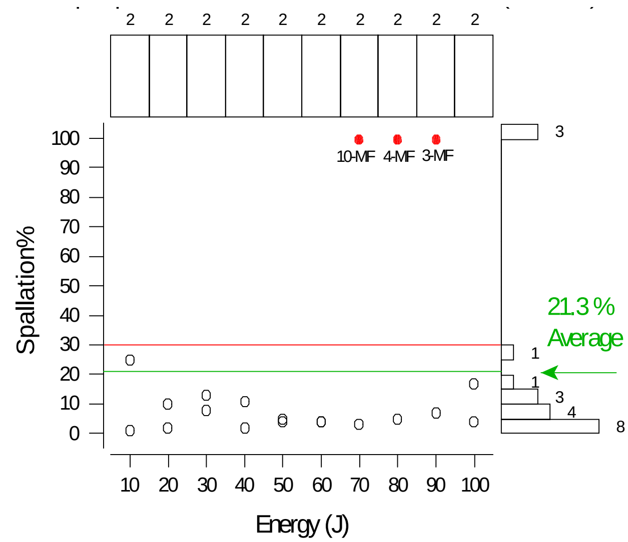

Fig 8. Drop-impact test results for a planar interface 1313 PDC cutter.

Fig 9. Typical example of general chipping or spalling cutter face damage.

Fig 10. Typical example of total fracture failure.

RESULTS

Eight PDC cutter designs were evaluated with the strain energy technique. The diamond-table thickness and the geometry of the diamond/carbide interface were the design variables. The diameter and overall height of each cutter were fixed at 13mm. Strain energy capacity was computed for each of the cutter designs tested. The value computed is the total strain energy stored in the quarter-section model. It can be assumed that the total strain energy absorbed by a whole cutter would be approximately four times the quarter section value.

Each design was then manufactured for laboratory evaluation of drop-impact resistance. Plots similar to Fig. 8 were generated for each cutter tested. An arithmetic average face-area spall value was then computed based on the results for each cutter. All of the PDC cutters were manufactured with identical diamond feedstock and substrate grade. Sintering process variables like time, temperature, pressure, etc. were comparable for each cutter type. Approximately 200 cutters were destructively tested for this comparison.

The computed strain energy capacity, equivalent static load, and subsequent average spall area from the drop-impact loss are listed in Table 2. The computed strain energy values are plotted against the average spall values in Fig. 11. Cutters with higher strain energy subsequently had higher impact resistance (less face-area loss). A least squares linear curve fit shows a positive correlation between strain energy and spall area. The agreement is relatively good (R^2=0.73). The computed static strength (equivalent static load) values are plotted against average spall in Fig. 12. The correlation is not as good as for strain energy (R^2=0.62).

Table 2. FEA model and impact-test results.

Strain Energy Capacity (mJ)	Equivalent Static Load Capacity (kN)	Average Face-Area Loss (%)
22.0	6.84	21.3
65.6	11.6	7.60
34.2	8.71	18.4
37.2	10.8	16.0
64.8	12.2	14.5
37.7	8.99	17.5
33.6	8.42	20.5
45.0	9.66	12.8

One factor strongly affecting the variations in strain energy capacity and static strength is the residual stress state. Cutters with high levels of residual compressive stress on the diamond surface are able to withstand higher static loads before reaching the diamond tensile limit. Cutters with thin diamond tables tend to have higher compressive residual stress on the surface. The diamond may be thin across the entire part or only thin in the region where the peak stresses occur. For example, a cutter with a hoop of diamond around the outer diameter and a thin layer over the center would also have high residual compressive stress on the surface. Thin cutters are less preferred in industry

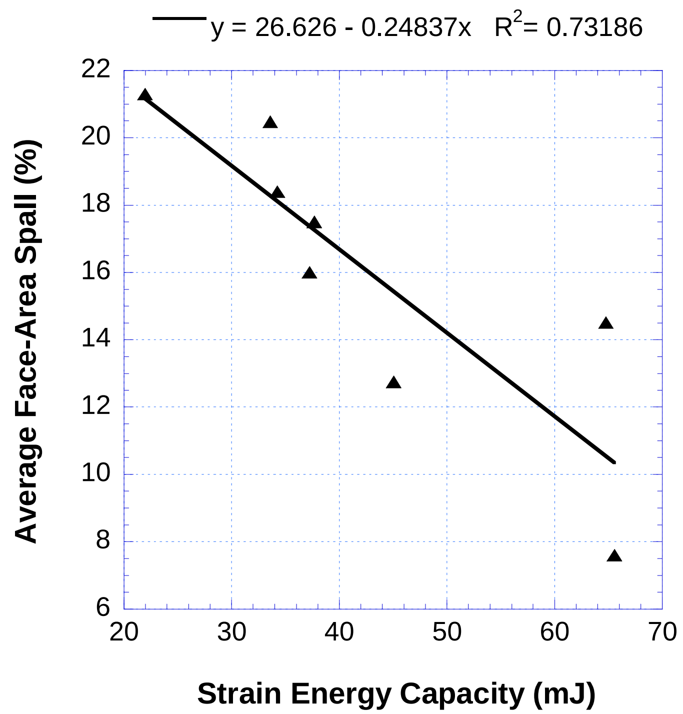

Fig. 11. Strain energy capacity – drop-impact resistance correlation.

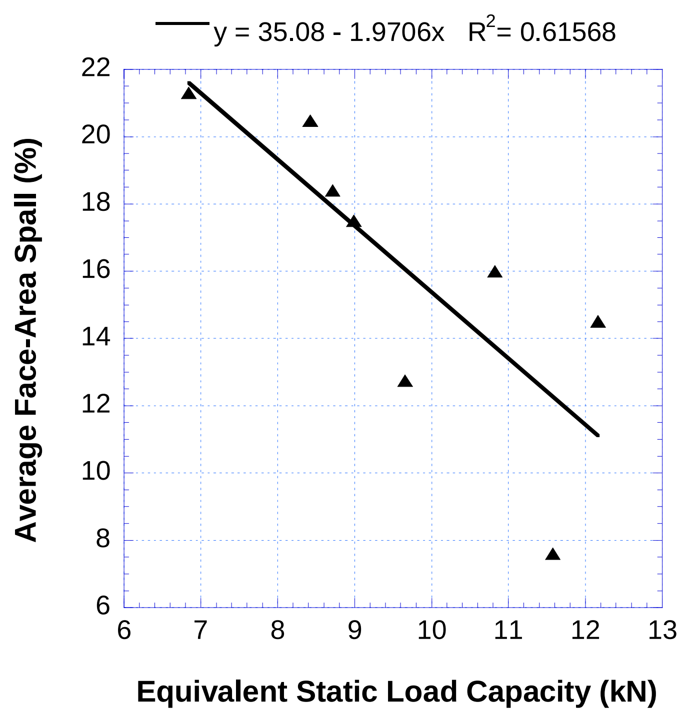

Fig. 12. Equivalent static load capacity– drop impact resistance correlation.

due to their reduced cutter life. The hoop design avoids this problem by providing more diamond on the cutter outer diameter. However, the hoop can cause problems during brazing. Most PDC bit manufacturers braze the cutters into pockets on the bit blades, subjecting the cutters to temperatures on the order of 800 ºC. Features that increase the room temperature residual compression on the diamond surface tend to also increase the braze temperature residual tension. The braze temperature tension can crack the diamond layer. Thus there must be some compromise between maximizing residual compression for impact resistance and making a brazeable PDC.

Another design variable important to the results is the interface geometry. As seen in Fig. 3, the stiff diamond provides relatively little energy storage compared to the carbide substrate. The cutter with the lowest calculated strain energy capacity in Table 2 has a planar interface. Replacing some of the diamond table with carbide via non-planar interface geometry can improve the energy storage. A combination of both diamond and carbide at the cutter interface effectively changes the material properties in this region. In addition, a non-planar interface can substantially alter the residual stress state and the stiffness of the diamond table. Manipulating the material properties and stiffness with interface geometry is the most likely reason for the difference between strain energy and static strength correlations with impact resistance.

Note that the calculated strain energy values are much lower than the laboratory drop-impact energy levels. Only a small percentage of the drop-tower load is absorbed by the cutters. Most of the impact energy is lost as plastic deformation of the strike plate. Deflection of the impact apparatus and rebound of the drop weight also rob impact energy. The practical implication is that the bit and bottom-hole assembly must absorb a significant amount of the impact energy because the cutters cannot.

While the correlation between impact resistance and strain energy is identifiable, it is not perfect. Manufacturing process variables present one source of error. Parameters such as sintering pressure, temperature, and time vary somewhat depending on the cutter design and geometry. Every attempt was made to control these differences in the test cutters. However, process variations may be responsible for the "outlier" toward the right side of the graph in Fig. 11. This cutter has a 4-mm thick diamond table and a special interface designed to minimize residual stress. Sintering extremely thick diamond PDC requires special processes. It is possible that the diamond-to-diamond bonding in this cutter was not as strong as in cutters with thinner diamond tables.

Another potential source of error is the FEA model assumptions. The axisymmetric boundary condition implicitly assumes a load is applied to both sides of the cutter. A more realistic boundary condition would be to model a half section of the cutter, leaving the end opposite the impact unloaded. It is not clear how to constrain this side since it merely rests against the steel fixture. Also, the equivalent static load was applied as a parabolically distributed pressure on the cutter edge. Other load distributions should be investigated.

Finally, condensing all of the laboratory drop-impact data into one number – the average percent spall – presents another source of error. This is an arithmetic average; so a few high spall failures are weighted more heavily than many beneficial low spall failures. Also, no weight is given to failures occurring at higher energy levels, which would indicate a tougher cutter. Cutter fracture is a highly probabilistic event. Impact test artifacts like strike-plate rebound add to the scatter in the data. Using a single number to represent such results can be problematic.

CONCLUSION

Using strain energy capacity as an index of fracture resistance under static and dynamic loading has proven effective. A positive correlation exists between numerical strain energy capacity calculations and laboratory measurements of impact resistance. This is quite a significant finding. The numerical models allow unlimited variations of design parameters to be investigated, pinpointing the critical variables without the need for expensive and time-consuming destructive tests.

In the near term we will continue to evaluate and test various cutter designs. We will also work on evaluating alternate boundary conditions and load distributions in the finite-element analysis to see what effect they may have. Finally, a new laboratory drop-impact test has been built with automatic rebound arrestors. This will eliminate strike-plate rebound and reduce the scatter in the data.

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