UNDERSTANDING AND CONTROLLING RESIDUAL STRESSES IN THICK POLYCRYSTALLINE DIAMOND CUTTERS FOR ENHANCED DURABILITY

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ABSTRACT

Residual stresses in PDC cutters arise from the difference in thermal expansion between the polycrystalline diamond layer and the supporting tungsten carbide substrate after sintering at high pressure and temperature. If not managed correctly, these stresses can significantly reduce the toughness of the cutters, especially as the diamond-layer thickness increases. Current industry trends favor thick diamond cutters to take advantage of increased cutter life. This paper outlines the potential benefits of using thick diamond layers and details a mechanism for mitigating the related high residual tensile stresses. Finite-element models, laboratory tests, and field results are presented.

SUMMARY AND CONCLUSION HIGHLIGHTS

Early attempts at US Synthetic to manufacture thick diamond PDC cutters with a flat interface resulted in delamination-type failures of the finished product. Residual stress was assumed to be responsible for these failures and cracks visible on the outer diameter of finished thick-diamond parts. Finite-element analysis was utilized to model the residual stresses present in PDC. Experimental measurements of surface residual stress agreed well with FEA model predictions when the model was subjected to a –650 °F temperature change. FEA models of thick diamond PDC showed a high tensile stress region in the diamond table above the interface on the cutter outer diameter. The location of this high tensile stress correlated well with observed cracks and fracturing after side impact loading. The models also revealed that a diamond hoop around the cutter perimeter with a portion of substrate material internal to the diamond table eliminated this harmful residual stress zone. Laboratory heavy-wear tests of .160-in thick PDC incorporating the diamond hoop produced a significant improvement in wear life, nearly five-times greater than a .030-in thick cutter. Subsequent field tests of the .160-in thick cutter confirmed the extended wear life observed in the lab. In addition, the delamination-type failure of flat-interface thick diamond was not observed with the hoop interface.

PRODUCTION OF THICK-DIAMOND PDC

Since their introduction over 20 years ago, polycrystalline diamond compact (PDC) cutters have gained wide commercial acceptance in the oil and gas drilling industry [1]. Bits equipped with PDC cutters now account for a significant portion of the total footage drilled [2]. Major advances in PDC performance have been achieved by adding non-planar interfaces between the diamond layer and substrate and by increasing the diamond thickness from the standard .030-in. US Synthetic has recently introduced a line of cutters with typical diamond thickness on the order of .160-in. Increasing the diamond thickness enables more diamond to be in contact with the formation during drilling, which increases wear resistance and improves the thermal characteristics of the cutter. However, tests have shown that as the diamond thickness increases the impact resistance or toughness of the cutter can be compromised.

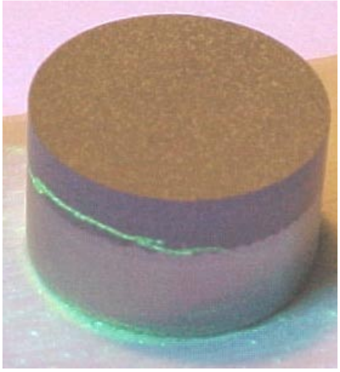

Fig. 1. Ultraviolet dye-penetrant test showing crack in PDC with a .120-in thick diamond layer.

Flat interface PDC cutters manufactured with a diamond layer thickness exceeding .100-in have a propensity to crack. The cracks form in the diamond table slightly above the diamond/carbide interface. A typical crack in a planar interface PDC with a .120-in thick diamond table is shown in Fig. 1. The cracking incidence increases as the thickness of the diamond table is increased. It was also found that these cutters fractured easily under a side-impact load. The impact failure appeared to originate at the same location as the crack. The subsequent fracture propagated roughly parallel to the interface, removing the entire diamond table. Residual stress was assumed to be responsible for this failure mechanism. Work was then initiated to accurately model the residual stresses in thick diamond cutters and determine a way to mitigate their harmful effects. This paper shows the reasons why thick diamond cutters delaminate and presents a way to control harmful residual stresses, a major obstacle to the production of thick diamond PDC.

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 to 70 kbar) [3]. The individual diamond crystals bond together and to the substrate under these extreme pressure and temperature conditions. As pressure is released and the PDC is allowed to cool, the diamond layer and substrate material respond at different rates, giving rise to residual stresses in the PDC.

Volumetric strain provides a simple model to illustrate the origin of these residual stresses. Assuming hydrostatic conditions and homogeneous, isotropic properties, the volumetric strain of a material can be written as

$$\mathbf{e} = \frac{3\Delta P(1-2\nu)}{E} + \alpha\Delta T_s \tag{1}$$

where $\mathbf{e}$ is the volumetric strain, ΔP is the sintering pressure change, ν is Poisson's ratio, E is the elastic modulus, and α is the coefficient of thermal expansion [4]. The sintering temperature change ΔT_s is defined in terms of the room temperature T and the sintering temperature T_s as

$$\Delta T_s = T - T_s \tag{2}$$

The first term on the right of Eqn. 1 represents the volumetric expansion of the PDC material as the pressure is released after sintering. The second term represents the volumetric contraction as the PDC material cools from sintering temperature to room temperature. Since pressure-induced volumetric strain has the same form as temperature-induced volumetric strain, the total volumetric strain can be written in terms of an "effective" temperature change as

$$\mathbf{e} = \alpha\Delta T_{eff} \tag{3}$$

In other words, a simple change in temperature can be used to model the combination of both pressure and temperature changes after sintering. We have found a good match between experimental measurements and numerical calculations of residual stress occurs when $\Delta T_{eff} = -650°F$. Thus the negative volumetric strain due to decreasing temperature is more dominant than the positive volumetric strain due to decreasing pressure.

A commercially available finite element analysis (FEA) package was used to model the residual stress in PDC cutters. The Pro/MECHANICA FEA package assumes linear static behavior of the materials and perfect attachment of the diamond layer to the carbide substrate. The model is constrained for free thermal expansion, and a temperature change is applied to all elements as in Eqn. 3. The material properties used for the analysis are listed in Table 1.

Table 1. Material properties used in FEA models [5,6].

	WC/Co	**PCD**
Elastic Modulus (psi)	7.91×10^{7}	1.24×10^{8}
Poisson's Ratio	0.22	0.22
Coefficient of Thermal Expansion ($\times 10^{-6}$ /°F)	3.3	1.3

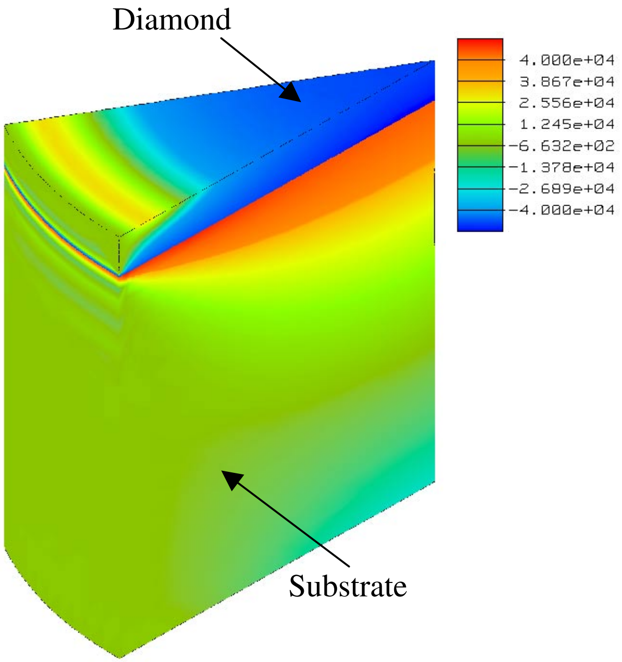

Fig. 2. Radial residual stress in a flat interface 1308 cutter with 0.030-in thick diamond table.

A three-dimensional residual stress model of a section of a flat interface 1308 PDC (∅.529-in x .315-in) with a .030-in thick diamond table is shown in Fig. 2. 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. Compressive residual stress in the brittle diamond layer is generally regarded as beneficial to increasing the PDC toughness.

To check the validity of the model, we measured the residual stress on the diamond table surface. A rosette strain gage (Micro Measurements model WA-06-030WR-120) was bonded to the center of the diamond table surface of a 1308 PDC cutter with a .030-in thick diamond table. The cutter was then held in a fixture while the carbide substrate was ground away. The strain gage response was recorded as a function of substrate thickness. The diamond is assumed to be stress-free when all the substrate material has been removed. The stress-free strain measurement is subtracted from all other strain values, producing a plot of surface residual stress as a function of substrate thickness. Experimental measurements, shown in Fig. 3, correlate well with published values [7].

At room temperature the PDC diamond surface is in compression when attached to the full substrate (point A in Fig. 3). The relatively thick carbide layer provides a stiff support to the PDC, preventing much bending from occurring on the free diamond surface. As carbide is removed, the diamond begins to expand outward, relieving some of this compression (point B in Fig. 3). In addition, the relatively stiff carbide support is being removed, allowing the diamond surface to bend slightly. Eventually enough carbide is removed to allow a significant amount of bending of the diamond surface. This bending is large enough to actually put the diamond surface into tension (point C in Fig. 3), an undesirable state for a brittle material. From this point on removing more carbide decreases the influence of the substrate on the diamond table. When the substrate is completely removed, the diamond table can expand fully, and the diamond surface is assumed to be stress free (point D in Fig. 3).

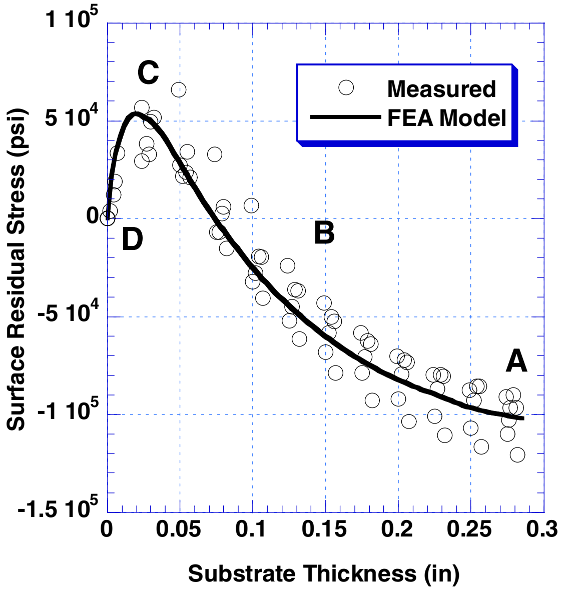

Fig. 3. Comparison of measured and computed surface residual stress in 1308 flat-interface PDC.

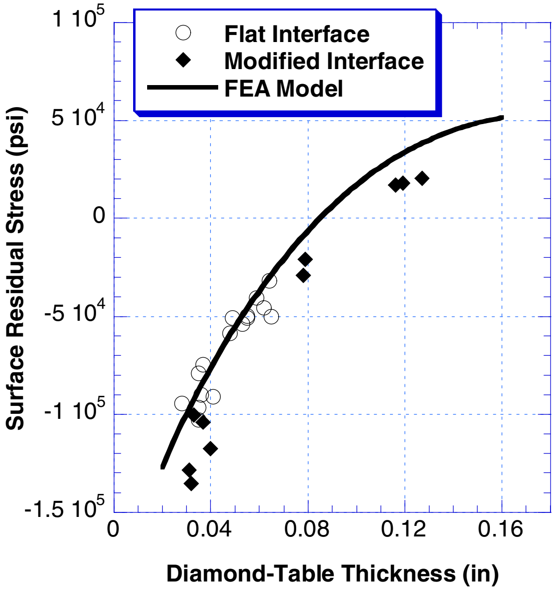

Fig. 4. Comparison of measured and computed initial surface residual stress in 1308 PDC.

FEA models were also made of flat-interface 1308 PDC cutters with increasing diamond thickness. A comparison of measured surface residual stress and FEA model results is shown in Fig. 4. The data points represent initial surface residual stress measurements made with the full substrate thickness (equivalent to point A in Fig. 3). Again the measurements on flat interface cutters agree well with the model predictions. The measurements on non-planar modified interfaces are slightly below the model prediction. The modified interface consists of parallel grooves approximately 0.010-in deep across the entire interface. A small amount of the modified substrate material remains attached to the diamond layer in these grooves at the end of the strain gage test. Thus the final strain-gage measurement is not actually the stress-free measurement, skewing the data toward higher initial compressive stress. Nonetheless, the model accurately predicts that increasing the diamond thickness reduces the compressive residual stress on the diamond surface. The diamond surface of the PDC cutter actually goes into tension for diamond thicknesses above approximately 0.080-in, a damaging condition for the brittle PDC material.

Good agreement between experimental measurements and calculations of residual stress demonstrated the accuracy of the FEA model assumptions. With this knowledge we were confident the FEA models could identify the residual stress components responsible for the cracks shown in Fig. 1. The first principal stress (maximum tensile stress) in a PDC cutter with a .160-in thick diamond table on a flat interface is shown in Fig. 5. Notice the very high tensile stress region on the cutter outer diameter just above the interface. This high tensile stress region correlates well with the location of the horizontal crack shown in Fig. 1. As the substrate contracts it tries to pull the diamond table with it. The diamond layers on the outer diameter of the PDC cutter are being strongly pulled downward by the retracting carbide. At the same time they are being pulled upward by the diamond table as it tries to expand outward. These two counteracting forces create the high tensile stress at the diamond edge. The direction of this tensile stress is nearly vertical. Notice also the tensile stresses present across most the diamond surface. The FEA models show tensile stresses exist on almost the entire diamond table surface in thick diamond cutters with the greatest magnitude on the outer diameter. Tensile stresses such as these in any brittle material can be extremely detrimental, decreasing the ability of the cutter to sustain high loads before fracture.

Since the harmful tensile stresses arise from the tug-of-war between the diamond and the carbide, a solution was sought to counteract the pull of the carbide substrate material. The residual stress models were used to rapidly screen alternative designs without the necessity of building and testing physical models. One solution discovered was to create a diamond hoop around the cutter perimeter with a portion of substrate material internal to the diamond table. The FEA model results for the hoop geometry are also shown in Fig. 5. The maximum tensile stress on the cutter edge has been reduced by

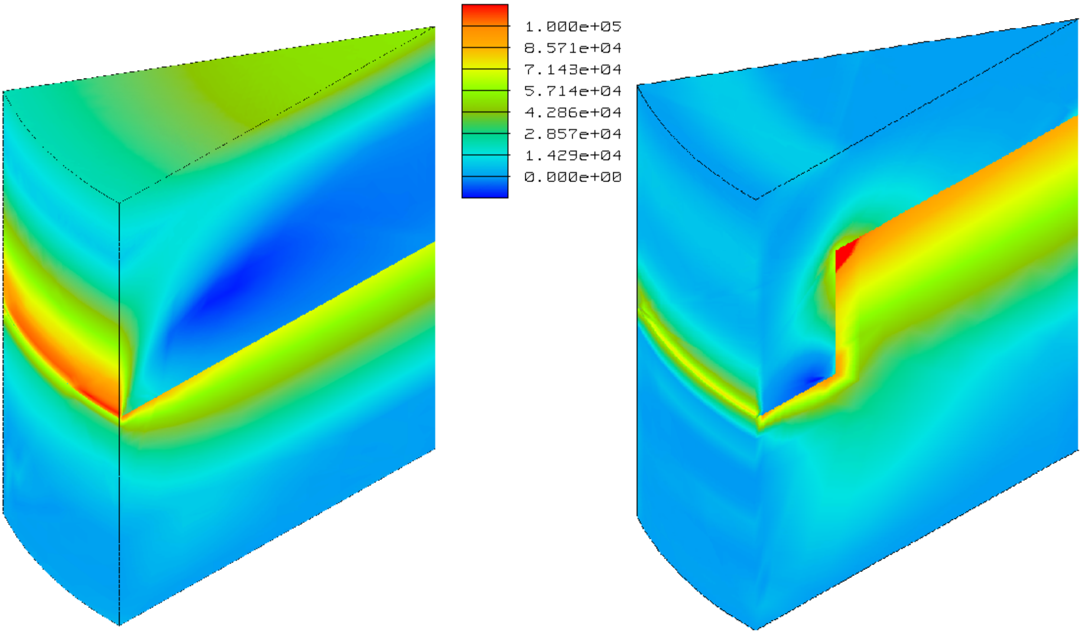

Fig. 5. Maximum tensile residual stress in 0.160-in thick diamond 1308 PDC cutters with a flat interface (left) and a non-planar hoop interface (right).

41% relative to a flat interface cutter with the same perimeter diamond thickness. The internal carbide feature of the hoop geometry counteracts the downward pull on the outer diamond layers, reducing the damaging tensile stress. Another benefit is the reduced tensile stress on the top diamond surface. The thinner diamond layer over the central region of the cutter creates more residual compression. Finally, the hoop geometry maintains the thick diamond region in contact with the formation during drilling. Comparison of residual stress in the two geometries shown in Fig. 5 clearly shows the overall tensile stress reduction afforded by the hoop geometry.

LABORATORY AND FIELD EVALUATION OF THICK DIAMOND PDC

Incorporating the hoop geometry into .160-in thick diamond cutters allowed them to be manufactured without generating cracks. This made laboratory and field testing possible. Sample cutters with .160-in thick diamond and the hoop geometry were subjected to our heavy-wear test. The heavy-wear test uses a vertical turret lathe to machine a 36-in diameter granite block with a PDC cutter. Cutting forces and wearflat size are measured throughout the test. The test continues until the cutter breaks, the wearflat intersects the steel fixture holding the cutter, or 30n passes across the rock have been completed. This test generates large wearflats on the PDC similar to wearflats generated in the field. The heavy-wear test parameters are listed in Table 2.

Table 2. Heavy-wear test parameters.

Parameter	Value	Parameter	Value
Rotary Speed	Constant 76 rpm	Linear Distance Cut	~ 41,000 ft (full test)
Cutting Speed	60-715 ft/min	Volume of Rock Cut	1160 in^3
Depth of Cut	.040 in	Rock Type	Sierra White Granite
Radial Feed Rate	.062 in/rev	Rock Unconfined	
Cutter Back Rake	20 deg	Compressive Strength	24,200 psi

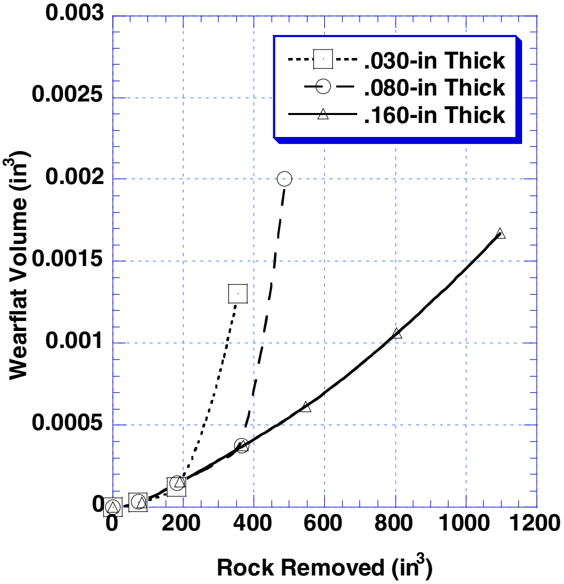

Fig. 7. Heavy-wear test results for 1308 PDC cutters with variable diamond thickness.

Wearflat volume is plotted against the amount of rock removed in Fig. 7 for 1308 PDC cutters with various diamond thicknesses. A .030-in thick diamond cutter with a flat interface wears steadily until about 200 in^3 of rock has been removed. At this point the wearflat begins to extend into the substrate. We speculate that wear into the carbide increases the frictional heat generated during cutting. This additional heat raises the diamond temperature and leads to rapid wear progression. The .030-in cutter test was stopped when a portion of the diamond table spalled and the wearflat extended into the support fixture. A .080-in thick diamond cutter with a flat interface wears steadily until approximately 400 in^3 of rock has been removed. At this point the wearflat begins to extend into the substrate, and subsequent wear is accelerated due to thermal effects. However, a cutter with a 0.160-in thick diamond table is able to wear steadily until the end of the test. The wearflat is contained within the diamond layer throughout the entire test, minimizing the frictional heat generated during cutting. The heavy wear test shows that .160-in thick diamond can provide extended wear life, up to five times greater than .030-in thick cutters.

The favorable lab results prompted subsequent field testing of the .160-in thick diamond. A proprietary non-planar interface incorporating the hoop design was developed for field testing. A Security DBS FM2665 bit was equipped with the test cutters and drilled in East Texas. The bit drilled approximately 1000 feet farther than offset bits with equivalent rate of penetration (ROP). The dull condition was also superior to offset bits. A photo of the worn bit is shown in Fig. 8. The wear is confined mainly to the diamond table with no evidence of chipping, spalling, or fracture in the diamond. The minimal wear and damage to the cutters enabled them to be rotated in the bit pocket and reused two more times in the same formation. Since this initial test more than 500 bits have been built and tested with the .160-in thick diamond. Using thick diamond PDC generally extends bit life without sacrificing durability or ROP. In addition, no delamination-type failures similar to those found in flat-interface thick diamond cutters have been observed.

Fig. 8. Photo of field worn 1913 cutters with .160-in thick diamond and hoop interface geometry.

CONCLUSIONS

Early attempts at US Synthetic to manufacture thick diamond PDC cutters with a flat interface resulted in delamination-type failures of the finished product. Residual stress was assumed to be responsible for these failures and cracks visible on the outer diameter of finished thick-diamond parts. Finite-element analysis was utilized to model the residual stresses present in PDC. A simple change in temperature was used to model the combination of pressure and temperature effects after sintering. Experimental measurements of surface residual stress agreed well with FEA model predictions when the model was subjected to a –650 °F temperature change. This means the PDC material contracts more from cooling than it expands from pressure release after sintering.

FEA models of thick diamond PDC showed a very high tensile stress region in the diamond table above the interface on the cutter outer diameter. The location of this high tensile stress correlated well with observed cracks and fracturing after side impact loading. The FEA models allowed us to explore various interface geometries with the goal of reducing the damaging stresses. One solution discovered was to create a diamond hoop around the cutter perimeter with a portion of substrate material internal to the diamond table. This internal carbide feature served to counteract the downward pull on the outer diamond layers, reducing the damaging tensile stresses. Subsequent manufacturing of .160-in thick diamond PDC with the hoop geometry revealed no evidence of residual stress cracking.

Laboratory heavy-wear tests of .160-in thick PDC incorporating the diamond hoop demonstrated a significant improvement in wear life. The thick diamond PDC machined nearly five-times as much rock as a .030-in thick cutter. The thick diamond is believed to extend wear life by delaying wearflat progression into the carbide substrate and the ensuing increase in frictional heat generation. Later field tests of the .160-in thick cutter confirmed the extended wear life observed in the lab. In addition, no delamination-type failures were observed in the field.

Accurate FEA models enabled US Synthetic to identify and mitigate harmful residual stresses in thick diamond cutters. The residual stress models were used to rapidly screen alternative designs without the necessity for extensive testing. We are currently developing new FEA techniques to evaluate the impact resistance and fracture toughness of PDC. We are also developing FEA models of combined cutting loads, thermal loads, and residual stress under simulated drilling conditions.

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