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THE DESIGN AND USE OF POLYCRYSTALLINE DIAMOND COMPACT DRAG BITS IN THE GEOTHERMAL ENVIRONMENT*

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MASTER

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ABSTRACT

The potential for utilizing polycrystalline diamond compact (PDC) cutters to provide high performance bits has been recognized by the drilling industry. New bit designs suitable for geothermal drilling are being developed based on the results of single cutter laboratory tests and analytical analyses. A new bonding technique for attaching the cutters to the bit body has been developed. Bits using this new technique have been built and tested with promising results.

INTRODUCTION

Drilling for geothermal resources is an extremely expensive procedure, due in part to the low penetration rates obtainable with conventional drilling bits in these hard formations. Bits utilizing PDC cutters have the potential for increasing penetration rate. The Department of Energy, through Sandia Laboratories, is performing research and development directed toward reducing the cost of drilling and completing geothermal wells. Under this program, Sandia Laboratories conducts both in-house research and external research at a number of industrial firms. As part of this program, the design of bits utilizing PDC cutters has received attention, both at Sandia and at the General Electric Corporate Research and Development Center. These activities have proceeded from single cutter tests to the design and testing of full-scale PDC bits.

Recently, bit designs using a full-face configuration of PDC cutters have been tested in the laboratory and under field conditions in a geothermal well. In addition, a hybrid bit design utilizing PDC cutters with a conventional roller cone has also been tested with encouraging results in the Panhandle Lime formations in Texas.

References and illustrations at end of paper.

This paper describes the results of single cutter tests, the bit design philosophy, the bonding process for attaching the cutters to the bit body, and the results of laboratory and field tests of these new bit designs.

SINGLE-CUTTER TESTS

A comprehensive series of cutting experiments utilizing single PDC cutters has been performed by Hibbs, et al.[1] The PDC cutters were bonded to tungsten carbide tool posts for the tests. Resultant forces on the cutter were measured for a range of rake angles from -5° to -30°. Marble, granite, and sandstone rocks were used. The compressive strengths of these rocks ranged from 10,000 to 50,000 psi. The results of these experiments, performed under atmospheric conditions, were used to design full-scale bits and to predict the horsepower requirements and penetration rates for the full-scale bits. The bits designed by GE were 8-3/4" in diameter and utilized a rake angle of 015°. The bits are designed such that each cutter experienced equal horsepower during rotation of the bit. These bits were fabricated and tested in the drilling laboratory at Tulsa University. The results indicated that the bit performance at atmospheric pressure could be predicted with a reasonable degree of accuracy using the results of the single cutter experiments. During the testing, however, some cutters were lost because of a failure in the bond between the cutters and the tungsten carbide tool posts. These tests indicated the need to develop a reliable attachment technique in order to properly utilize the PDC cutters in high performance bit design.

The cutters on these bits were attached using a conventional low-temperature brazing technique. Following these tests, General Electric initiated a program to improve the braze and the brazing technique to provide higher shear strengths at the elevated

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temperatures which would be encountered in geothermal drilling. In a parallel program, Sandia Laboratories initiated the development of an attachment technique, called diffusion bonding, that could be used to attach the cutters to either tungsten carbide tool posts or to the bit body directly. This technique has been described previously by Jellison[2] and Huff[3] and will be briefly summarized later in this paper.

Using the diffusion bond, PDC cutters bonded to tungsten carbide tool posts were prepared for use in single-cutter tests. These tests were designed to fully evaluate the effect of rake angle on the forces on the diameter cutter.[4] A fully instrumented cutter bar which would hold the PDC cutters securely at different rake angles, and would yield dynamic data of the horizontal, vertical, and lateral forces acting on the cutting element during the cutting operation was designed and fabricated. Rock samples (approximately 3'x3'x2.5') were mounted on the table of a King vertical milling machine. These test rocks were rotated at surface speeds of 120 ft/min at the cutter position. Cuts of various depths, rake angles and cross feeds were made in St. Cloud Grey Granodyorite (41,000 psi compressive strength), White Sierra Granite (28,000 psi), and Texas Pink Granite (23,000).

During the initial tests which were performed using the cutters with the manufactured rake angle of -5°, a cutter failed and a carbide stud holding the cutter sheared. Investigations indicated that the failure occurred in stages. The diamond surface failed first, causing the cutting forces to rise, and the higher forces then caused the mounting stud to fail. Analysis of the data indicated that the diamond face was failing (spalling) in shear due to high forces tangent to the diamond surface. Tests at increasing the negative rake angles indicated that in strong rocks, rake angles of less than -20° could result in this type of failure of the diamond, and that at negative angles greater than 30°, the diamond surface and supporting carbide substrate were slowly worn away resulting in a self-sharpening action. In the single-cutter tests conducted in this experiment, the diffusion bond proved to be of sufficient strength while the conventional braze joint used often failed.

The results of these tests were incorporated into a full-face PDC cutter drill bit design, and a computer program[5] was used to determine the placement of the cutters to provide for equal volume of rock removed per cutter per revolution. A picture of a 4-3/4" bit design using the technique is shown in Figure 1. This bit was designed and fabricated at Sandia.

ATTACHMENT TECHNIQUE

Before proceeding to a discussion of bit design and testing, a discussion of the diffusion bonding attachment technique is appropriate. In this technique, the surfaces to be joined are cleaned, and in some cases metallized, and then pressed together at a pressure of approximately 30,000 psi at 650°C for four hours. In order to provide for intimate contact between the two surfaces to be joined, the parts are placed inside an evacuated, collapsible can and are surrounded by a pressure transfer medium, such as graphite granules. Using this technique, shear strengths in excess of 65,000 psi in the weld zone are routinely obtained. The surfaces to be joined are in complete contact, and the impurities on the surface diffuse into the base materials at the bonding temperature to allow the surfaces to fay.

Previous work[2,3] has been directed at attaching tungsten carbide tool posts to the tungsten carbide substrate upon which the polycrystalline diamond compact is grown. This procedure involves metallizing both surfaces with a thin layer (25 μm) of nickel. It was recognized, however, that the use of steel tool posts rather than tungsten carbide could result in a much lower cost for the bit. It was further known that bonding of metallized PDC to steel studs was feasible. Additional bonding experiments were performed to determine whether the metallization procedure was actually required to achieve adequate bonding on steel studs. In these experiments, various combinations of Ni, 1040 Steel, and 4340 Steel tool posts were mated with metallized and unmetallized PDC's. Steel would be expected to weld better than nickel because of its ability to assimilate contaminants and to reduce surface oxides. The welds formed between steel and carbide were observed to have shear strengths in excess of 65,000 psi even when the surfaces were unmetallized. This finding represents a significant breakthrough in the bonding of Stratapax cutters to drill bits. It indicates that the process of metallizing both surfaces can be eliminated while at the same time maintaining adequate strength in the bond. There is some concern, however, that the thermomechanical properties of steel tool posts could result in residual stresses being created during the bonding process. The lower modulus of the steel could conceivably allow sufficient flexing of the system and cause cracks to form in the PDC thus weakening the cutting structure. Analyses are underway to evaluate this situation.

The ease of weldability to PDC's is only one of the advantages of steel over carbide as a mounting material. The cost, ease of fabrication, availability, and lack of a stringent flatness requirement on the bonding surface all make steel desirable. Considerable effort must still be expended to determine if steel gives adequate physical support to PDC's. However, some testing of bits using PDC's attached to steel tool posts has been conducted, and these results are described in the next section.

LABORATORY TESTING OF DRILL BITS

Laboratory tests of bits built with diffusion bonded PDC cutters are being conducted. The purpose of these tests is to demonstrate the integrity of the bonds and to evaluate and develop design criteria for high performance drill bits using PDC cutters. To date, tests of two all-PDC bits (4-3/4 [Figure 1] and 6-1/2 inches in diameter) and a 7-7/8 inch hybrid roller-cone-PDC bit (Figure 2) have been conducted. The tests of the 6-1/2 inch and hybrid bits were parametric studies of bit performance as a function of wear. The 4-3/4 inch bit was tested in a severe overstress condition to determine the ultimate stress levels that the cutters can withstand.

The procedure used in the parametric tests is to drill in Carthage Marble at various loads to obtain rate of penetration (ROP) and torque data. Drilling is then conducted in Sierra White Granite to wear the cutters, and the parametric tests are repeated in the marble. With this approach, the effect of wear on ROP and torque can be determined. The ROP versus load for the 6-1/2 inch and the hybrid bits are shown in Figures 3 and 4. The wear for the 6-1/2 inch bit was accomplished by drilling approximately 10 feet in granite while the hybrid drilled two 5-ft intervals with an intermediate parametric test in marble after the first interval. As expected, the load required to maintain a given ROP increases with cutter wear.

The ROP of the 6-1/2 inch bit varies linearly to 10 fph and increases quickly to a higher ROP for all wear conditions. The slope of the curve is greater after the step increase in ROP for all cases. In the final wear condition, the rate of increase begins to fall off at higher ROP, probably because the wear flats on the studs are interferring with penetration.

The torque required to rotate the 6-1/2 inch bit in various rocks and wear conditions is shown in Figure 5. The important thing to observe is that the torque is basically a function of load for all wear conditions. The torque required on 4 runs in granite varied insignificantly even though the wear was significant in this period. The ROP varied from 27 fph for a 10,000 lb load down to 11 fph for the same load at the end of the test. For the hybrid bit, torque varied insignificantly for the three wear conditions in Carthage Marble.

FIELD TESTING OF DRILL BITS

Laboratory testing of PDC drill bits has proven to be an effective tool for assisting in the design of new bits. Based on the results of these laboratory studies, a series of field tests are being conducted to demonstrate the viability of the PDC cutter in severe environment drilling. These tests are being conducted at several locations under various operating conditions.

General Electric, under contract to the Department of Energy, designed an 8-1/2" diameter all-PDC bit. The bit was fabricated by Smith Tool Company and is shown in Figure 6. This bit was tested in a geothermal well in New Mexico in November of 1978. In this well, the bottomhole temperature was approximately 250°C at a depth of approximately 6,000 ft. The drilling fluid used was a mist. After varying the weight on bit through a wide range of values and obtaining no footage drilled, the bit was pulled and examined. Catastrophic failure of the tungsten carbide tool posts which were supporting the PDC cutters was evidenced as shown in Figure 7. Several cutters were removed from the bit and sectioned in the hopes of determining the cause of the catastrophic failure. A microscope photograph of a sectioned cutter is shown in Figure 8. A crack emanating from the base of the cutter into the tungsten carbide tool post is clearly evident. The cause of the failure of the bit is therefore attributed to stress buildup along this crack which caused the cutters to fracture very early in the test. Further examination has revealed evidences of braze in this crack, indicating that the damage occurred to the tool post before or during the brazing operation. The reason for the crack origination is attributed to the pocketed design of the stud used in this application. An improved stud design utilized by Sandia is shown in Figure 9 along with a picture of the pocketed stud. Current thinking is that the pocket in the tungsten carbide tool post causes a stress raiser to be generated at the back of the pocket. The new stud design offers the potential for circumventing this problem.

In order to test the diffusion bonding technique, the hybrid bit shown in Figure 2 was tested in a gas well in Wheeler County, Texas, in May, 1979. The bit used steel tool posts. The formation drilled was Panhandle Lime at a depth of slightly over 1400 feet. On the particular hole in which the bit was tested, lost circulation was occurring. The bit was run into the hole at 1418 feet and drilling began with almost total lack of fluid return and with no return of any cuttings.

After varying the weight on bit and rotation rate to find the optimal drilling conditions, steady-state conditions of 20,000 lbs weight on bit and 50 rpm were selected for the remainder of the run. Fluid flow was restricted to less than 200 gal/min because of the lost circulation problem.

A rate of 50 ft/hr was achieved and maintained at the low flow rate. Increasing the flow rate to 350 gal/min increased the penetration rate to above 65 ft/hr, but because of the increased fluid loss, the flow rate was reduced to the original level. A total of 230 feet was drilled when all available fluid was used. Penetration rates achieved were between two and three times as high as the conventional bits normally used in this drilling application.

Upon recovery of the bit it was determined that half of the cutters were severely chipped and two cutters were completely missing with part of the PDC substrate still attached to one tool post. The bit had continued to drill well even with the missing cutters. Analysis to establish the reasons for the cutter damage is underway. The bond strength allows fairly small pieces of cutter to be retained while drilling, but continued chipping can result in the total loss of a cutter, even if it is well attached.

An attempt was made to follow this bit with another bit having tungsten carbide tool posts. However, problems relating to lost circulation terminated the test before drilling could be achieved.

Based on the results of this field test, it appears that steel tool posts have the potential for performing well in bits using PDC cutters; however, additional analysis and testing is needed to insure that the steel adequately supports the PDC substrate and that cutter breakage can be prevented in future bit designs. Toward this end, a detailed analysis of stress induced in the cutter has been initiated.

STRESS ANALYSIS

In order to properly design the tool post used to support PDC cutters, calculations of the stress induced into the tool by the tool/rock interaction are necessary. A computer code called TOODY has been utilized to provide transient analysis of stresses induced in the tool. The calculation utilizes a biaxial tensile fracture model to treat rock failure. Figure 10 shows how the problem is modeled. The computer model uses a finite difference technique for computing the stresses in the rock and in the tool. The tool and rock models are covered by a grid, and stress calculations are performed over each grid given the cutting force, the thrust force, and the characteristics of the rock. The modeling of this problem is in the early stages of development and will eventually be applied to rocks of interest in geothermal drilling. However, in the initial calculation, rock properties corresponding to sandstone were chosen. The properties are as follows: density of 2 gm/cm^3, sonic velocity of approximately 2 kilometers/ec, poisson ratio of .1, and tensile strength of 100 bars.

Figures 11-13 show the calculated development of damage (tensile fractures) during the first 70 microseconds of loading. As the tool moves into the rock face, tensile fractures develop beneath the tool (see Figure 11) and propagate away from the surface as shown. The tool cutting force increased steadily during this stage of the problem as indicated by the dot density plots (Figures 11-13) on the tool structure. The dots indicate points at which the stress exceeds 100 bars in the tool. As loading continues, fractures are seen to develop in the rock ahead of the tool (see Figure 12) and propagate in roughly spiral fashion toward the rock surface (see Figure 13). At the same time these lateral fractures are developing, the calculated tool force shown in Figure 14 is decreasing rapidly. This calculated tool force history agrees in in a qualitative sense with force histories obtained in actual rock cutting experiments (see Figure 15).

TOODY has the capability to model the drag tool/rock interaction problem. Future work in this area will investigate: 1) quantitative agreement between calculated tool forces and that obtained in single cutter tests, 2) stress state in the tool and efficiency of rock removal for various rake angles, depths of cuts, cutting speeds and rock types, 3) modification of the problem setup to treat effects of confining pressure on the rock surface, and 4) extension of the present tensile failure model to include shear type failures in the rock.

It is felt that the utilization of this analytical capability will provide for the determination of stresses induced in the tool as a function of rake angle and should lead to the optimal design of the cutting structure.

CONCLUSIONS

Preliminary results from laboratory testing of polycrystalline diamond compact drill bits indicate a significant potential for increasing penetration rate with bits of this type. The main problem areas which have been identified during this testing phase are: 1) the attachment of the cutters to the tool post or to the bit body directly, and 2) the potential for tool post breakage in field drilling operations. Approaches to solving these problems are presently being pursued and a resolution of these difficulties appears to be obtainable. The potential for utilizing PDC bits on high-speed downhole motors and in hard rock drilling will be the focus of future development activities.

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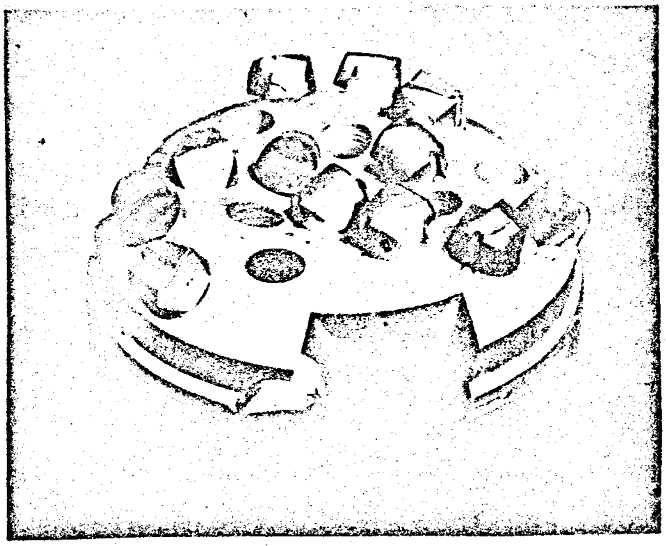

Figure 1. 4-3/4" all-Stratapax bit

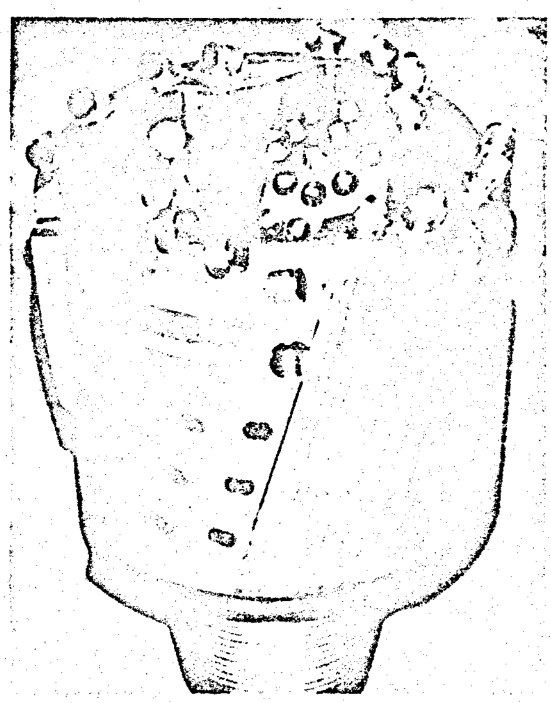

Figure 2. 7-7/8" hybrid bit

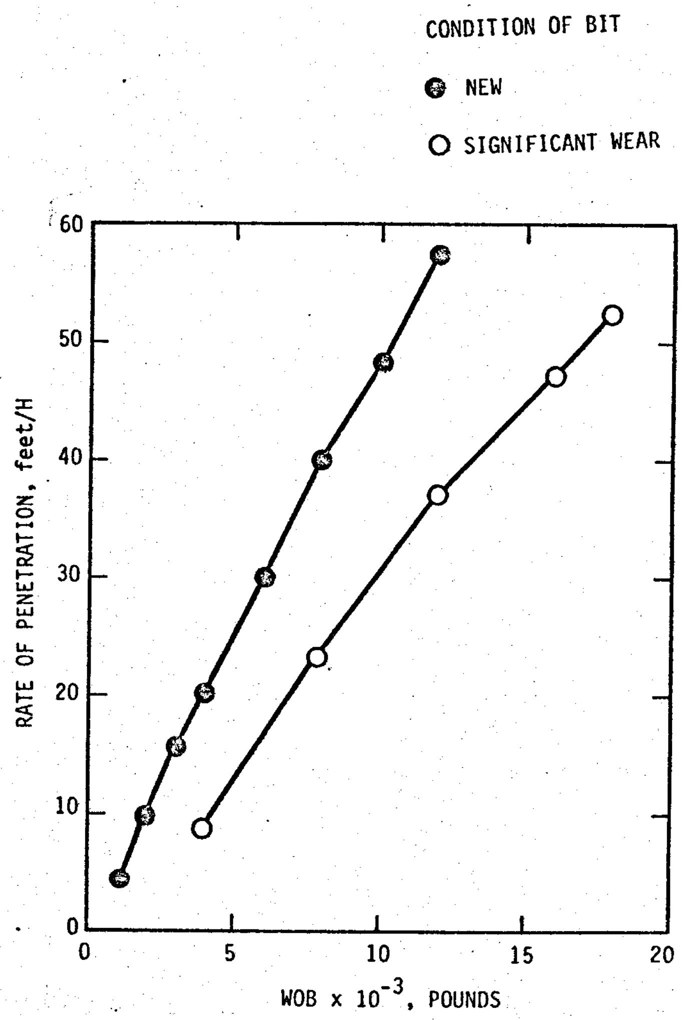

Figure 3. Performance of 6-1/2" PDC bit in Carthage Marble

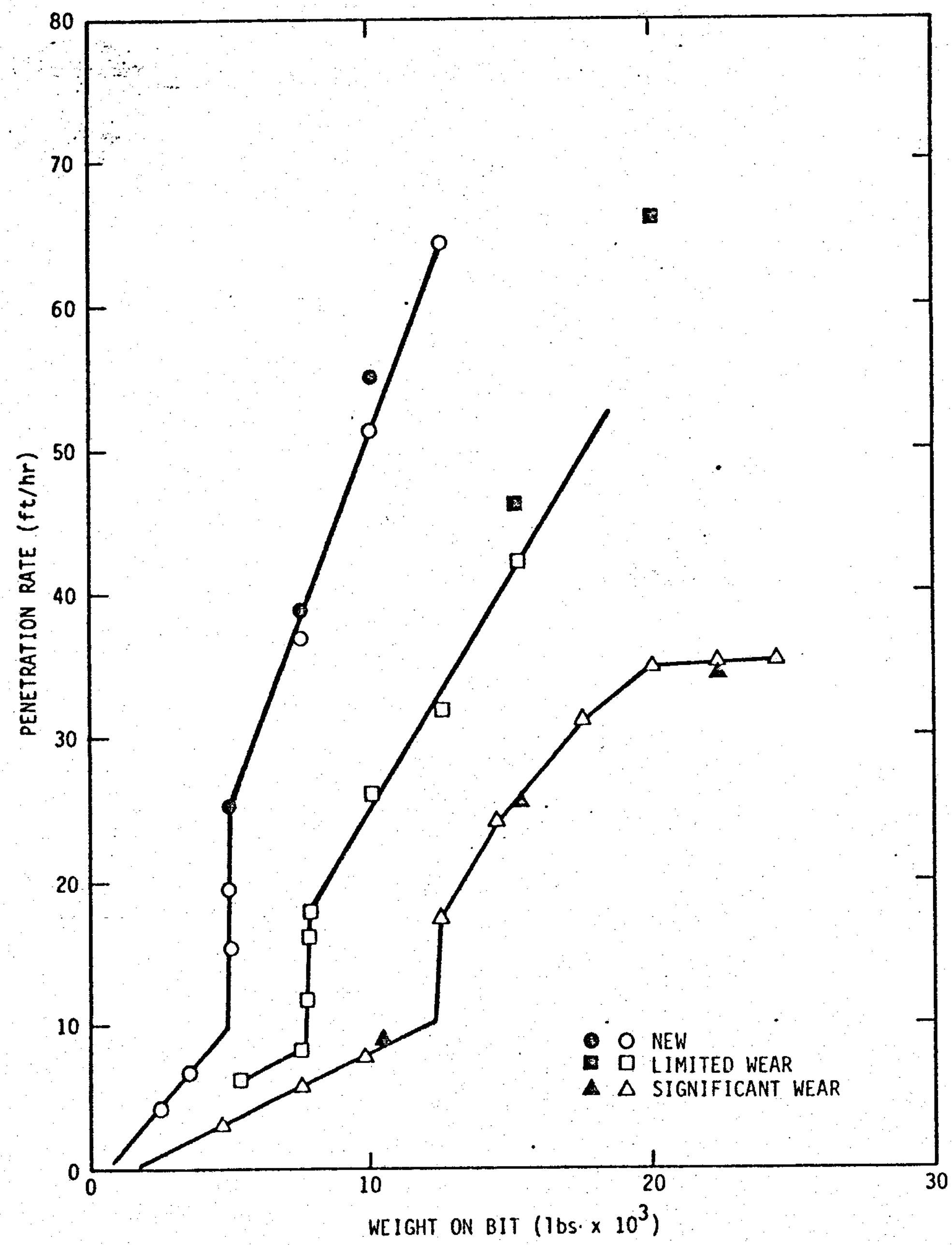

Figure 4. Performance of hybrid bit in Carthage Marble

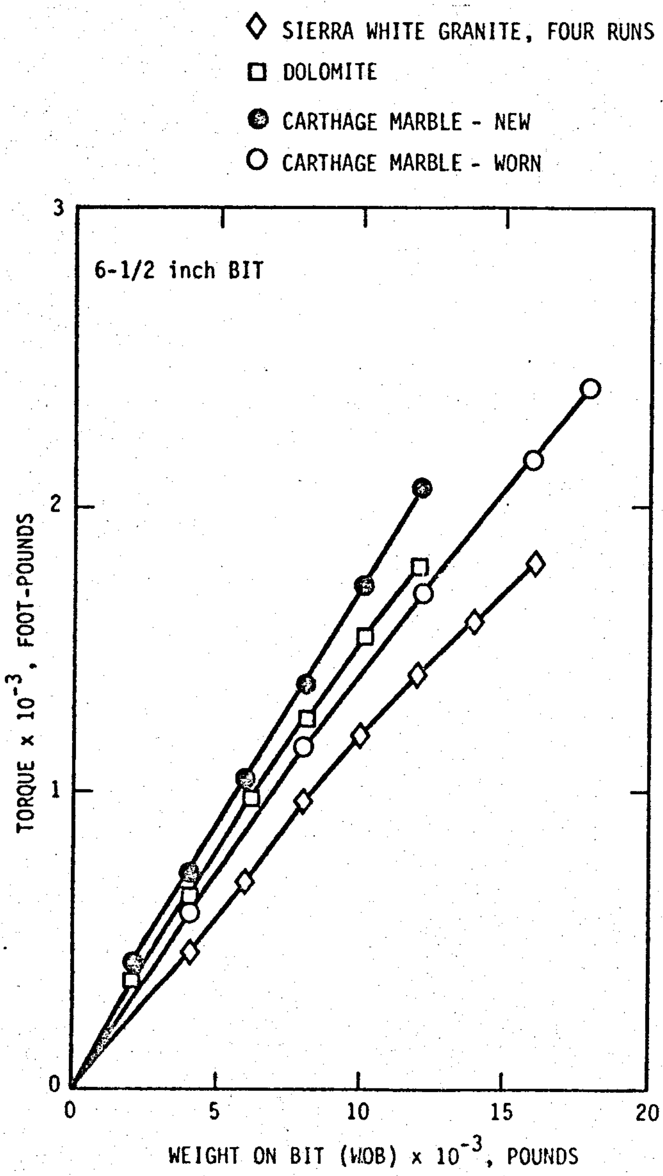

Figure 5. Torque characteristics for a PDC (6-1/2") bit

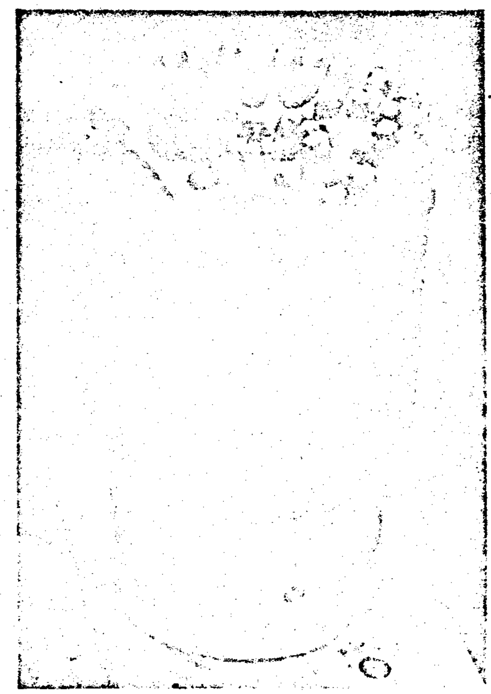

Figure 6. Stud-type PDC bit

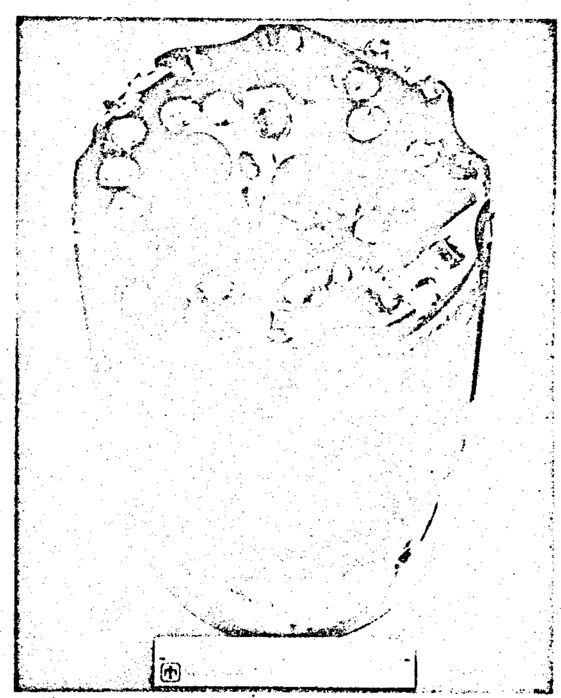

Figure 7. Stud-type PDC bit after field test

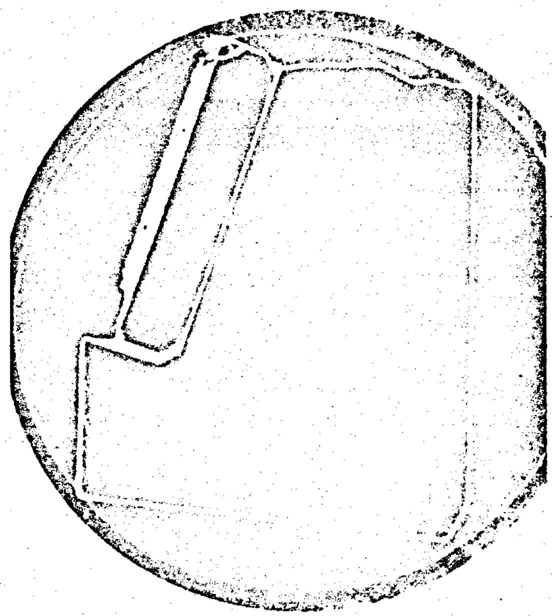

Figure 8. Microscopic cross section of damaged PDC cutter

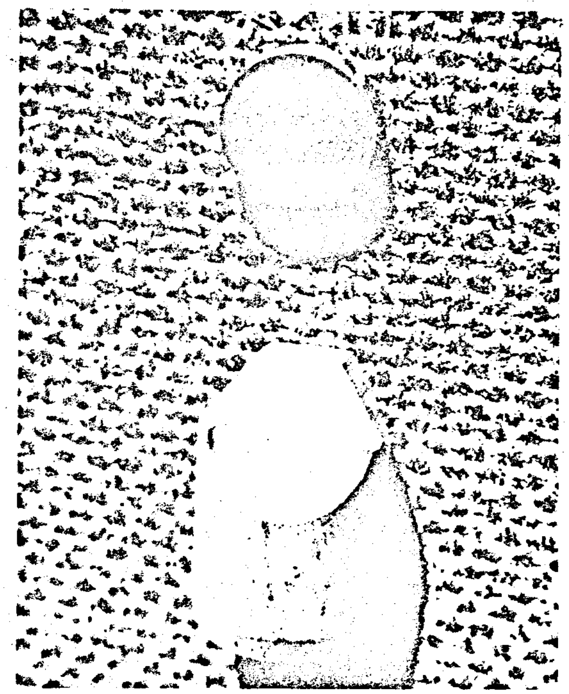

Figure 9b. Pocketed stud design

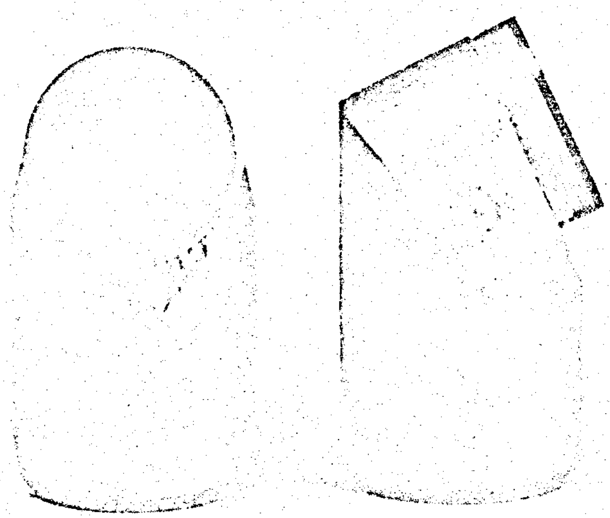

Figure 9a. Sandia stud design

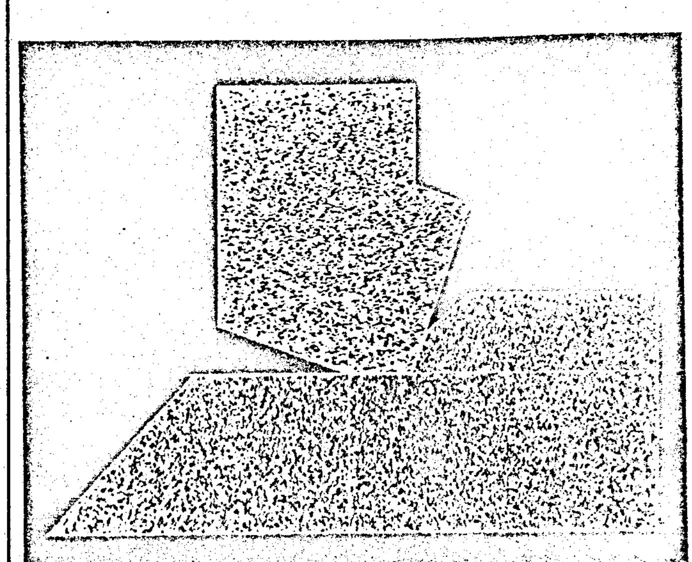

Figure 10. Stress in tool and rock at 25 μsec

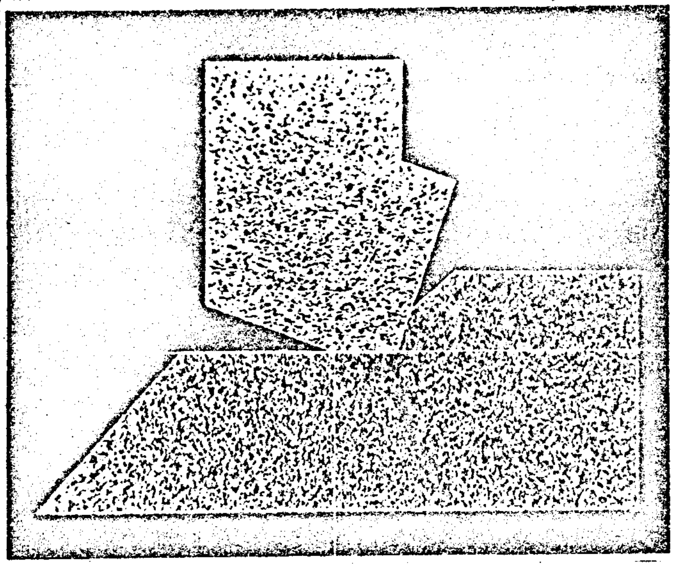

Figure 11. Stress in tool and rock after 50 μsec

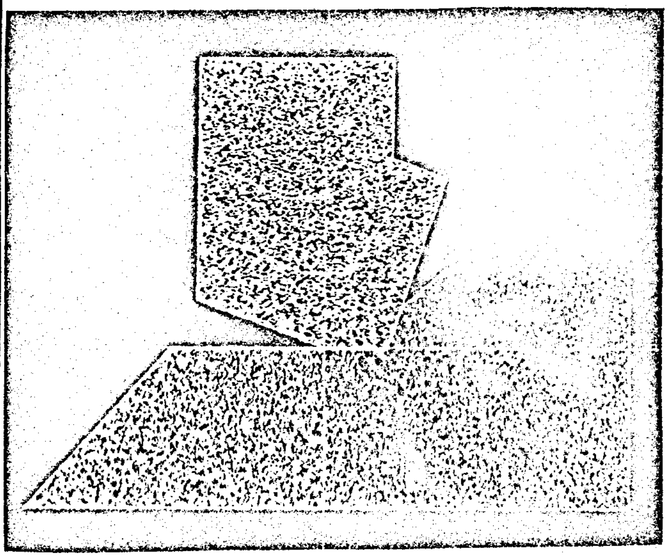

Figure 12. Stress in tool and rock after 70 μsec

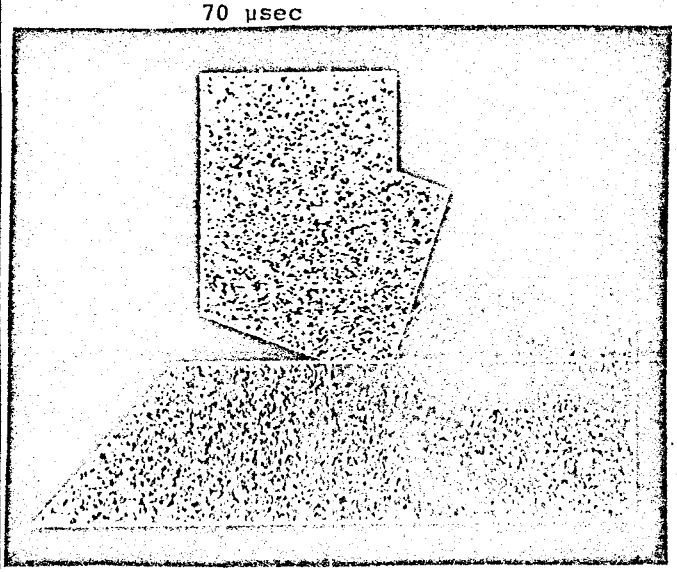

Figure 13. Stress in tool and rock after 85 μsec

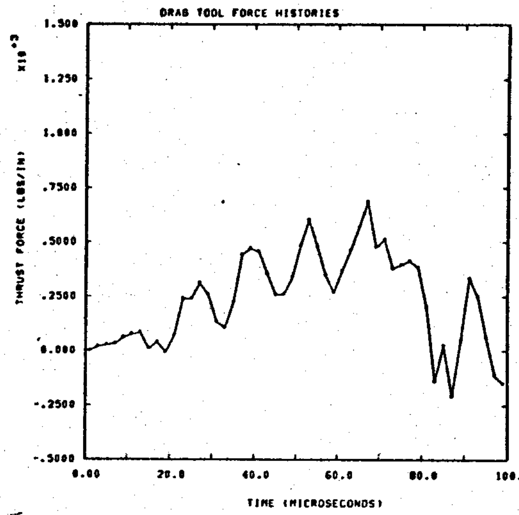

Figure 14. Calculated cutting force history for drag tool

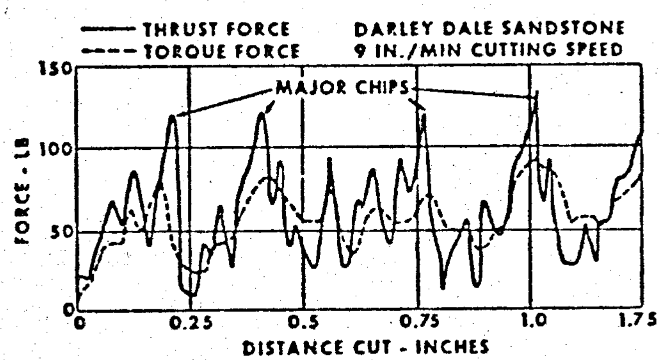

Figure 15. Experimental force-displacement curves for drag cutting of rock at atmospheric conditions