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MASTER

Failure Mechanisms of Polycrystalline-Diamond Compact Drill Bits in Geothermal Environments

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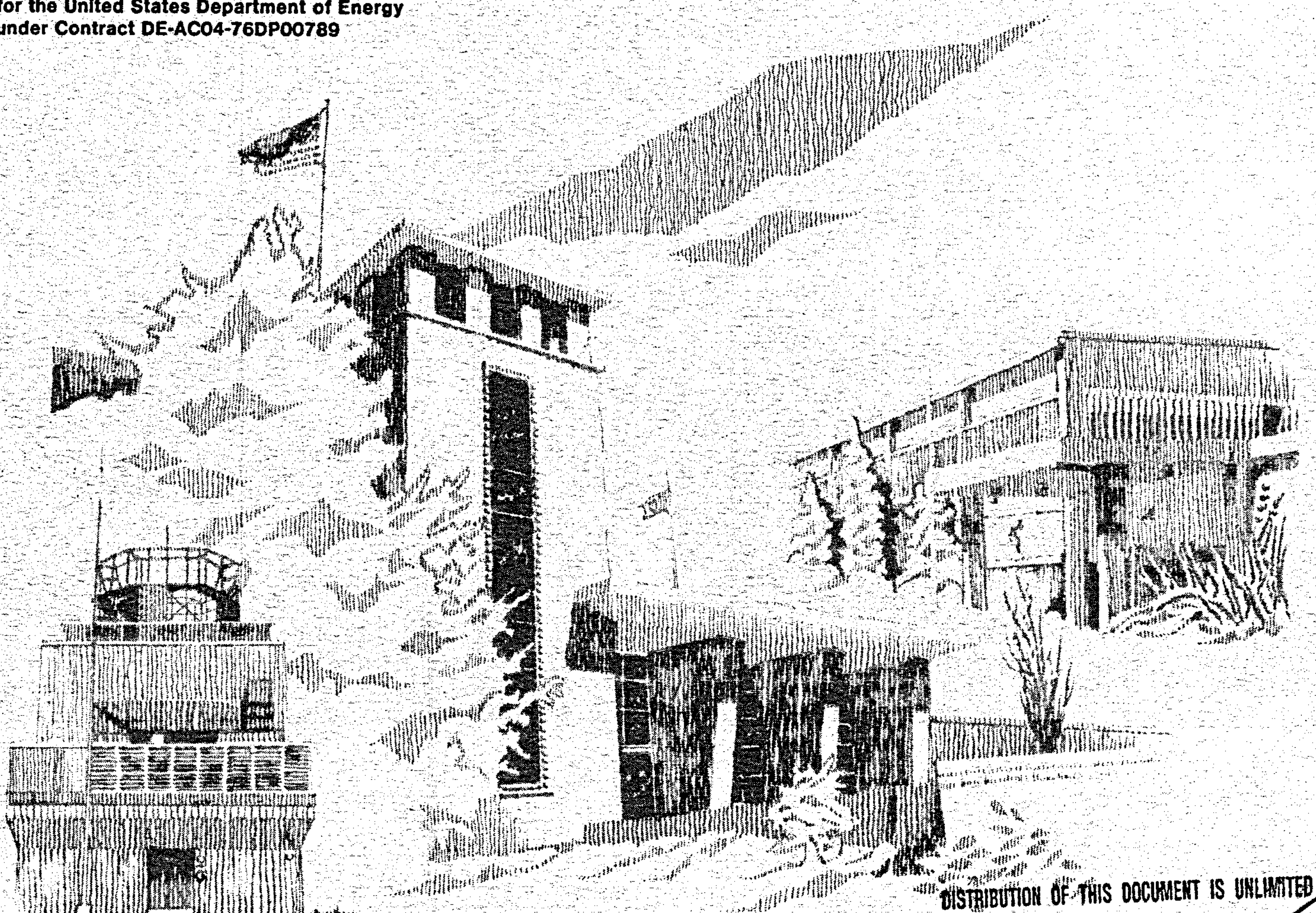

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FAILURE MECHANISMS OF POLYCRYSTALLINE-DIAMOND COMPACT DRILL BITS IN GEOTHERMAL ENVIRONMENTS

Ed R. Hoover
Larry E. Pope

ABSTRACT

Over the past few years the interest in polycrystalline diamond compact (PDC) drill bits has grown proportionately with their successful use in drilling oil and gas wells in the North Sea and the United States. This keen interest led to a research program at Sandia to develop PDC drill bits suitable for the severe drilling conditions encountered in geothermal fields. Recently, three different PDC drill bits were tested using either air or mud drilling fluids: one in the laboratory with hot air, one in the Geysers field with air, and one in the Geysers field with mud. All three tests were unsuccessful due to failure of the braze joint used to attach the PDC drill blanks to the tungsten carbide studs. A post-mortem failure analysis of the defective cutters identified three major failure mechanisms: peripheral nonbonding caused by braze oxidation during the brazing step, nonbonding between PDC drill blanks and the braze due to contamination prior to brazing, and hot shortness. No evidence was found to suggest that the braze failures in the Geysers field tests were caused by frictional heating. In addition, inspection of the PDC/stud cutter assemblies using ultrasonic techniques was found to be ineffective for detecting the presence of hot shortness in the braze joint.

ACKNOWLEDGMENT

The authors acknowledge the contributions of M. M. Sturm in obtaining SEM photomicrographs and of J. L. Jellison for photomicrograph interpretation.

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INTRODUCTION

During the past few years drag-type drill bits utilizing polycrystalline diamond compact (PDC) cutters have met with considerable success in drilling oil and gas wells in both the North Sea and continental United States [1]. To date, these drill bits have been most successful in relatively soft formations such as shale, claystone, and siltstone. However, the drilling industry and the Department of Energy (DOE) have recognized the potential of PDC drill bits for significantly reducing the cost of drilling geothermal wells via increases in the bit life and penetration rates.

This interest led to a research program to develop PDC drill bits suitable for the severe conditions encountered in drilling geothermal wells. The research has included both analytical studies and single-point cutter tests as well as full-scale drilling tests in both the laboratory and the field [2,3].

Recently, two different GE/Smith PDC drill bits were tested using air as the drilling fluid--one in the laboratory and the other in the field in northern California at the Geysers geothermal field. Another PDC drill bit built by the Strata Bit Corporation was tested on a turbine at the Geysers using mud as the drilling fluid. Both bits tested at the Geysers were unsuccessful. A post-mortem failure analysis of the PDC cutters was conducted at Sandia to identify the critical mechanisms that caused these bits to fail prematurely.

This paper describes these full-scale bit tests, presents the conclusions of our failure analysis, and makes corrective recommendations.

SUMMARY OF DRILLING TESTS

To avoid damaging the producing formation in geothermal areas such as the Geysers, air is normally used as the drilling fluid in the lower portion of the well, where bottom-hole temperatures often exceed 500°F. Therefore, in order to evaluate the performance of PDC bits in this type of drilling environment, a GE/Smith drill bit was tested in the laboratory under atmospheric conditions using preheated air as the drilling fluid. Subsequently, two other bits were tested at the Geysers using air and mud as the drill fluid.

GE/Smith Laboratory Test

The full-scale laboratory drilling test was performed at the Drilling Research Laboratory in Salt Lake City in February 1980. Using an air flow of 900 cfm and a gas-fired heat exchanger, the inlet air temperature was maintained at approximately 480°F.

The stud-type 8 1/2 inch diameter PDC drill bit used in this experiment was successfully field tested in October 1979 in the Baca geothermal field in northern New Mexico [4]. Originally, all of the PDC drill blanks were mounted on -20° back rake tungsten carbide (WC) studs using the General Electric developed LS brazing process (see Figure 1). Prior to the hot air laboratory test, five of these cutter assemblies were replaced because they had significant wear. On three of the new assemblies the PDC drill blanks were LS brazed to -25° WC studs. On the other two the PDC drill blanks were mounted on -25° steel studs using a diffusion bonding process developed at Sandia [5]. The locations of these cutters are shown in Figure 2.

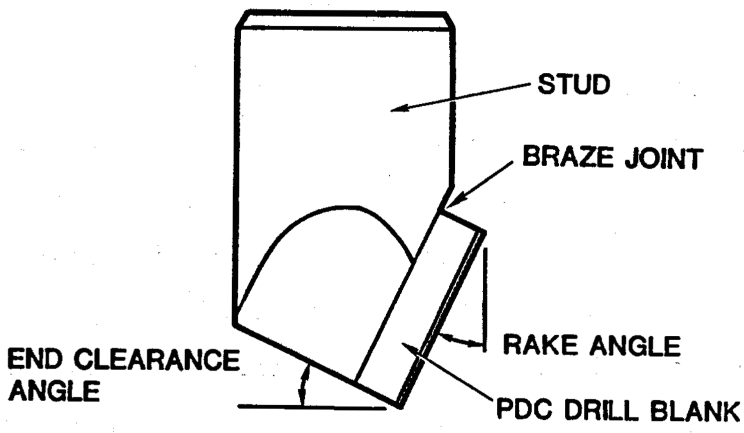


Figure 1. PDC/Stud Cutter Assembly
(Note: The PDC drill blank consists of a 10 mil thick diamond layer bonded to a cemented carbide substrate.)

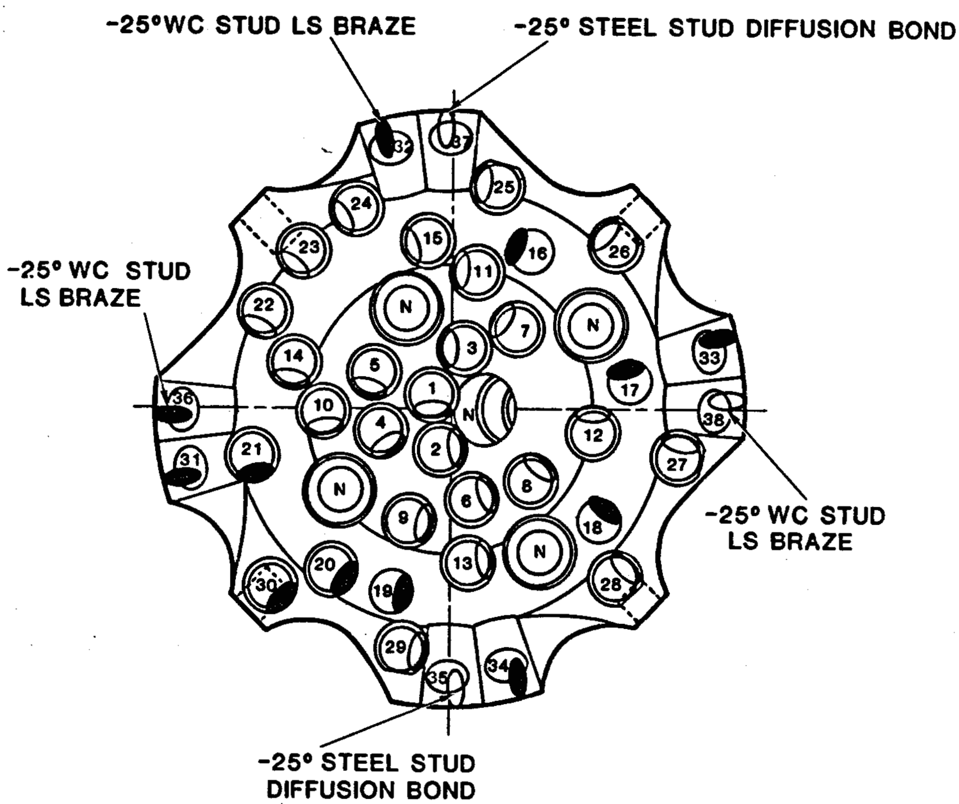


Figure 2. Modified GE/Smith bit which lost twelve PDC drill blanks during the hot air laboratory test.

After successfully drilling four 30 inch deep holesin Nugget sandstone (unconfined compressive strength of 18,000 psi), the bit was carefully examined. No measurable wear of the polycrystalline diamond compacts was found. However, many of the -20° back rake cutters on the crown of the bit had significant wear on the top and outer edge of the carbide stud behind the PDC drill blank. None of the -25° studs had any top or side wear. This is most likely because the -25° studs have an end clearance angle of 25° while the -20° studs have an end clearance angle of only 5°.

The GE/Smith bit was then tested in Sierra White granite which had an unconfined compressive strength of 24,000 psi and a relatively large grain structure. After drilling the first 30 inch hole, examination showed significant wear of many of the outer cutters. In addition, there was some localized high frictional heating indicating inadequate cooling by the air drilling fluid. The procedures used to drill the first hole in the granite were repeated for the next hole. While drilling only 6 ft/hr at 50 RPM with a bit weight of 35,000 lbs, the bit failed catastrophically. Twelve LS brazed PDC drill blanks were detached from their stud support structures. Eleven of these compacts were recovered intact from the parking lot, where the hot air exhaust had ejected them.

The cutters that lost their PDC drill blanks are shaded in Figure 2. Both of the diffusion bonded -25° steel cutters remained intact even though they were worn severely.

In general, the air drilling performance of the GE/Smith bit in the Nugget sandstone was very promising. The bit exhibited almost no PDC wear after drilling a total of 10 feet under very adverse conditions. At the time the hot air test in the granite was considered to be "overkill". Therefore, the decision was made to conduct a full-scale air drilling field test of a GE/Smith PDC bit, provided the -25° back rake studs were used instead of the -20° studs.

GE/Smith Geysers Test

On October 19, 1980 an 8 3/4 inch diameter GE/Smith PDC drill bit was tested in a Union geothermal well at the Geysers field in northern California. On this particular bit the innermost fourteen PDC drill blanks were LS brazed to -20° back rake tungsten carbide studs while the remaining 25 drill blanks were LS brazed to -25° back rake tungsten carbide studs.

At the time of this test the well was producing steam from the highly fractured Graywacke sandstone formation (unconfined compressive strength of 37,300 psi). The well depth was 6700 feet with a bottom-hole temperature of approximately 480°F. An air flow of 2300-2400 cfm was used for cooling and cuttings removal.

The new GE/Smith drill bit entered the hole smoothly and only had to ream the last 30 feet. After touching bottom the rotary speed was set at 55 RPM and drilling was commenced with a bit weight of 5000 lbs in order to establish a new bottom-hole pattern. After rotating for approximately 10 minutes without any measurable penetration, the bit weight was increased to 25,000 lbs in 5000 lb increments. There was still no measurable penetration. The rotary speed was increased to 80 RPM with up to 20,000 lbs on the bit without any noticeable improvement; hence, the experiment was halted.

Inspection of the bit revealed that 14 of the outermost -25° studs had lost their polycrystalline diamond compacts and were severely worn. The tungsten carbide studs of the nine outermost cutters were actually worn flush with the steel bit body (refer to Figure 3). The other five studs were worn progressively less toward the center of the bit. None of these 14 studs appeared to have been fractured or broken. In addition, three of the four gauge trimmers mounted on the side of the bit had also lost their PDC drill blanks.

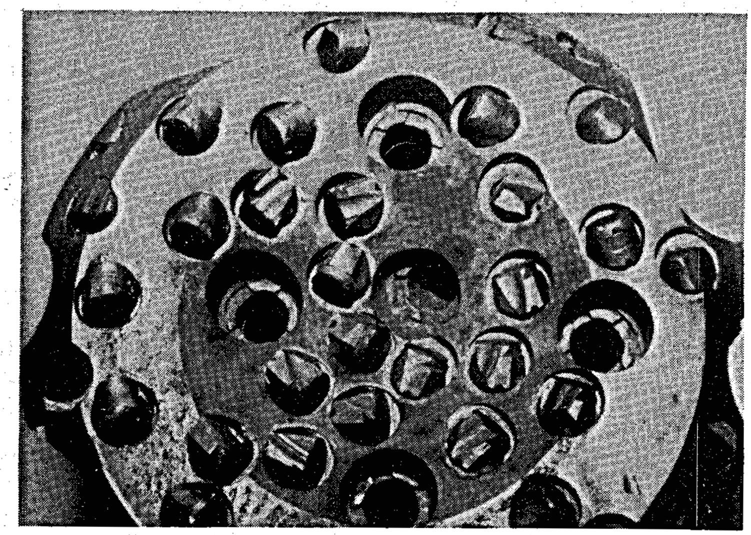


Figure 3. GE/Smith bit after the Geysers air test

Strata Bit Geysers Test

On November 7, 1980 a 12 1/4 inch diameter PDC drill bit manufactured by the Strata Bit Corporation was tested at the Geysers in the upper portion of Union's Angeli #2 geothermal well. All of the PDC drill blanks on this bit were LS brazed to the -20° back rake carbide studs. In general, the bit's design (body profile, material, etc.) was very similar to the GE/Smith bit pictured in Figure 3.

The bit was run on a 7 3/4 inch diameter Eastman downhole turbine using a 9.1 lb/gal mud instead of air as the drilling fluid. A 2° bent sub located just above the turbine/drill bit assembly was used to orient the bit in the proper direction.

The drill bit reached bottom in the greenstone formation at a total depth of 1600 feet. The bottom-hole temperature at this depth was below 150°F. After orienting the bent sub and setting the flow rate at 550 gpm, the bit was eased on bottom with a bit weight of 5000-10,000 lbs. After 15 minutes without any measurable penetration, the entire drilling assembly was rotated from the surface at 40 RPM to enlarge the hole and allow the turbine to begin to run freely. A total of four feet was drilled; however, since the turbine was unable to drill any footage without rotating the entire drill string, the test was terminated. Apparently, the turbine bearings and hole were too tight to drill using this particular drill bit.

Initial inspection of the Strata Bit PDC drill bit revealed that four cutters had lost their PDC drill blanks while the other cutters appeared to be in excellent condition with very little spalling or wear. Later, in the laboratory, all of the remaining cutters were examined ultrasonically to evaluate the braze joint integrity; five braze joints were suspected to be weak. Two of these suspect bonds were so poor that the PDC drill blanks were easily removed using a pair of vise grips. The locations of these cutters are shown in Figure 4.

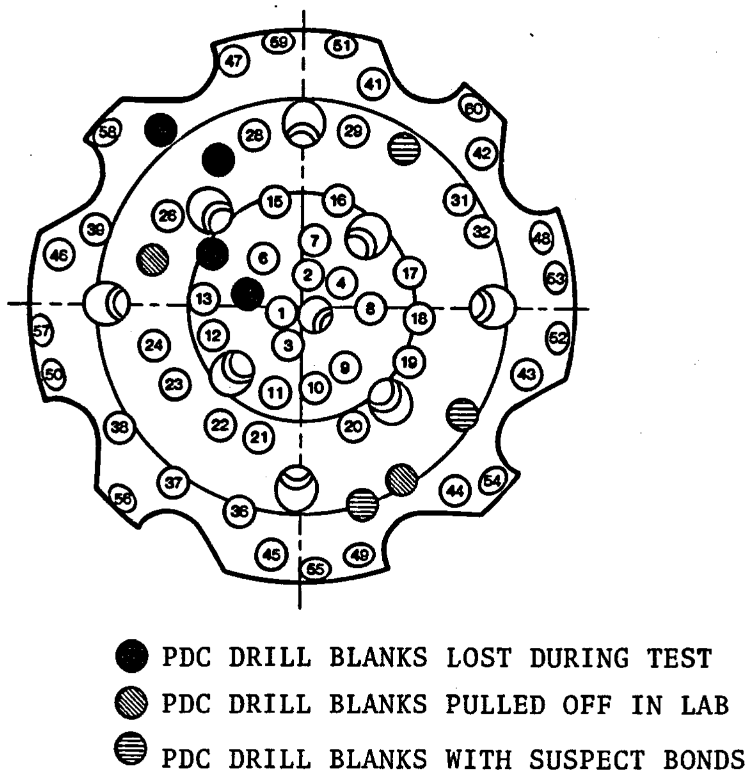


Figure 4. Location of cutters on Strata Bit Corp. drill bit lost or damaged during the turbine test at the Geysers.

POST-MORTEM FAILURE ANALYSIS

Low magnification visual examinations and ultrasonic testing were used to select PDC cutters and studs for diagnostic evaluations. Electrical discharge machining through the stud, which preserved the integrity of the braze joint, was used to detach studs and cutter elements from the bits. Failure surfaces were characterized using the light microscope and the scanning electron microscope (SEM). Information gained from these tests and drilling histories was used to identify failure mechanisms.

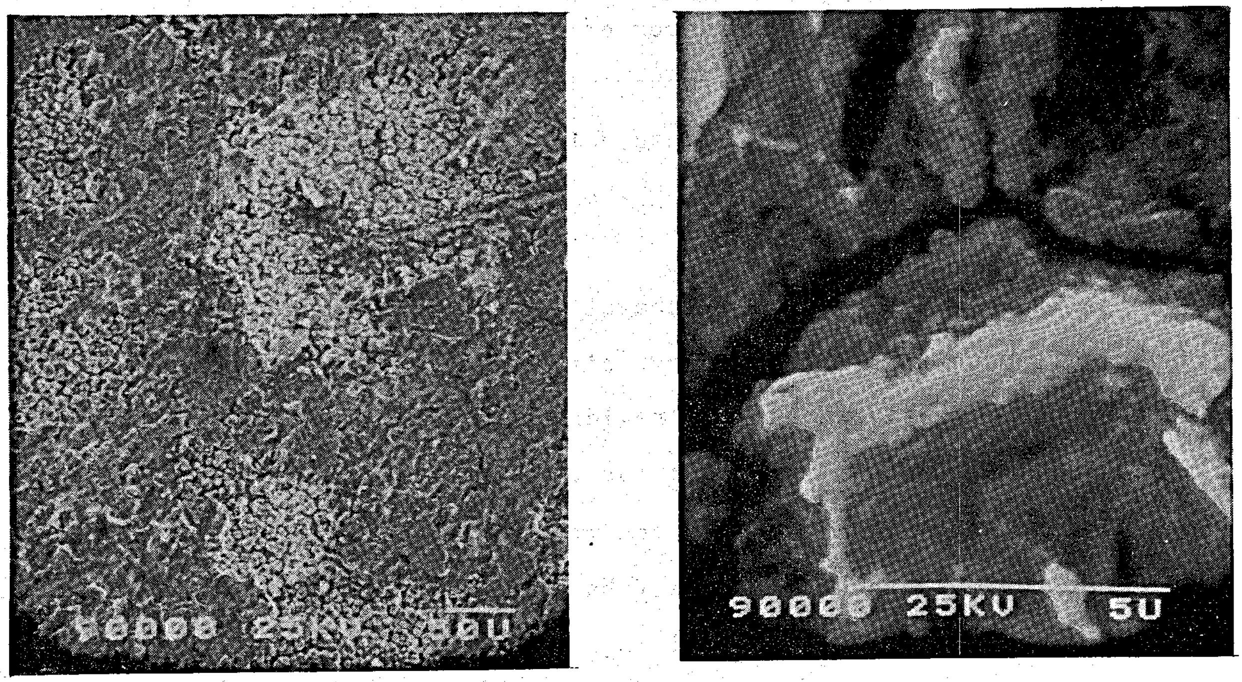
GE/Smith Laboratory Test

Six of the eleven PDC drill blanks recovered after the drill bit failed catastrophically were examined at low magnification in the light microscope. Five drill blanks showed extensive plastic deformation in the cemented carbide substrates beneath the polycrystalline diamond layers, while the sixth sample had a fractured edge negating any plastic flow determination--the deformation layer had probably spalled off. The plastically deformed cemented carbide layers extended 0.15 to 0.30 inches beneath the wear flat surfaces; distances which are rather large for cemented carbide cutting tools. Temperatures above 1550°F are required before plastic deformation of this magnitude is to be expected.

Diamond layers, at least on the wear flats, would have been heated to a temperature of the same magnitude as that required to produce the observed plastic deformation in the cemented carbide. Thermal damage in the diamond layers was evaluated using ultrasonic and silicon carbide grit blast tests [6]. No bulk thermal damage was found; however, the wear flat surface had a severely thermally degraded diamond layer, see Appendix A for more details and photomicrographs. Bulk diamond layer temperatures must have been less than the maximum safe temperature, nominally 1300°F, whereas frictional heating had raised the wear flat temperature significantly above 1300°F. Temperatures above 1300°F cause the binder phase in the diamond layer to degrade resulting in binder phase erosion, diamond crystalline pullout and a very rapid wear rate. Large wear flats had been formed even though only 50 inches of Sierra White granite was drilled.

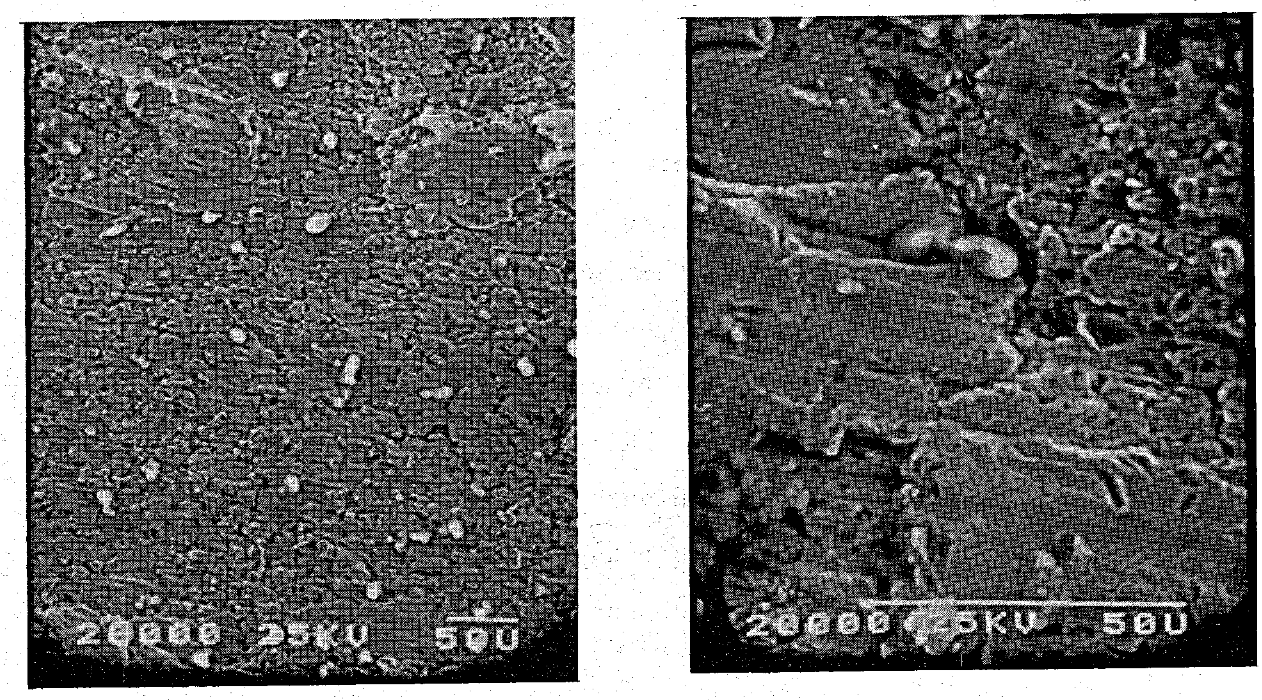
Three PDC drill blanks were selected for evaluation in the SEM. One specimen showed poor periphery bonding in excess of 15% of the total available area, but this was not considered to be a significant factor in the failure of the drill bit. The primary failure mode was hot shortness within the braze; extensive hot-short regions were found on each of the three PDC drill blanks. Hot shortness occurs when liquid films are formed along some of the grain boundaries resulting in an instantaneous loss of strength. Grains slide on the liquid film and the part separates. Cracks are developed at the grain boundaries. Typical photomicrographs illustrating these points are shown in Figure 5; Figure 5(a) shows the extensive nature of the hot shortness, and Figure 5(b) shows cracks at the grain boundaries. A less common but still typical hot shortness region is shown in Figure 6. Nodules approaching a spherical shape are dispersed across the surface, see Figure 6(a). At higher magnification, Figure 6(b), the nodules are identified as liquid droplets extruding out of grain boundaries. Little evidence was found of high temperature ductile rupture.

A commercially available copper-manganese-cobalt braze alloy [7] was used to bond PDC drill blanks to cemented carbide studs. The listed solidus and liquidus temperature is 1645°F and 1830°F, respectively. Analysis of braze constituent binary phase diagrams [8] suggests that a low melting phase field existed in this alloy, a concept which was supported by energy dispersive spectroscopy (EDS) data. Composition inhomogeneities were rather severe when grain boundaries and bulk regions



(a) (b)

Figure 5. Typical hot shortness observed on PDC drill blanks used in the hot air laboratory test; (a) 200x (b) 10,000x



(a) (b)

Figure 6. Less common hot shortness observed on PDC drill blanks in the hot air laboratory test; (a) 200x (b) 1000x

were compared. Similar differences existed between nodules and the matrix near the nodules. The rather wide melting range (185°F) and the low melting phase field could cause hot shortness. Hot shortness has been documented in a similar alloy where nickel was substituted for the cobalt. [9].

The PDC bit tested in the laboratory with hot air failed catastrophically due to grain boundary melting, i.e., hot shortness. The existence of extensive hot-short regions precludes the possibility that these hot-short regions existed prior to testing; the bit would not have survived the initial test cycles and regions of ductile failure would have been found where bit integrity had existed. The test was considered a success in that it defined drilling conditions and strata where the bit performed well. Drilling conditions used for Sierra White granite pushed the bit beyond its temperature capability, which helps define regions where PDC cutter bits using copper-manganese-cobalt brazes will not perform well.

GE/Smith Geysers Test

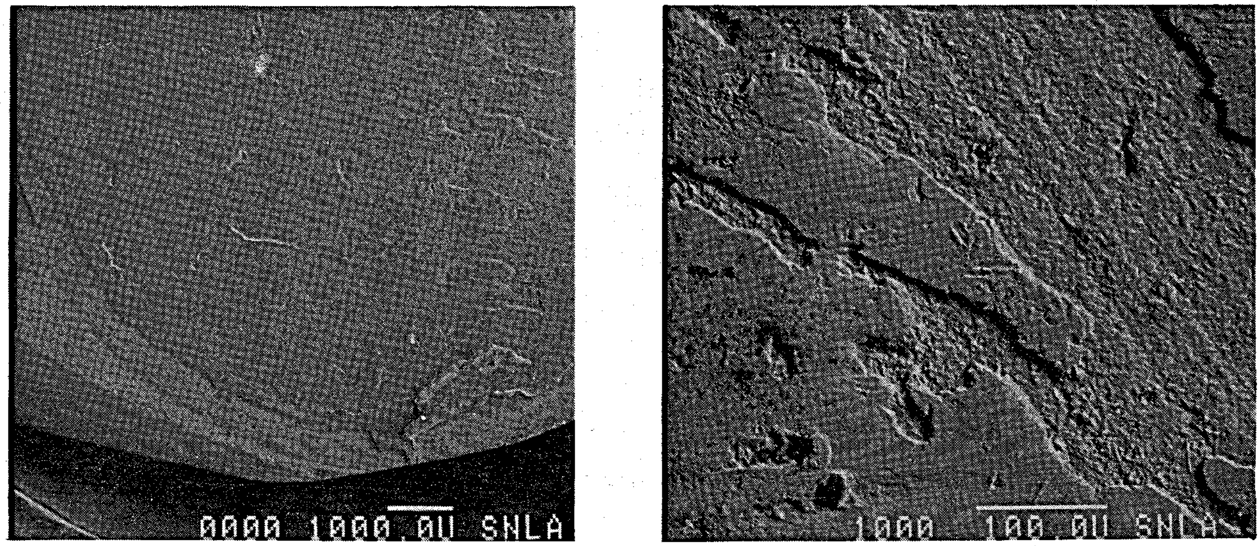
Fourteen PDC drill blanks were lost during the Geysers air test. An unaided eye examination indicated that the gauge row cutters were most probably lost first with other cutters being lost sequentially from the outside toward the inside of the bit. No evidence of stud fracture was found. Wear flats on intact PDC cutters and on studs which had lost PDC drill blanks were typical of that produced by an abrasive grinding action. Based on the PDC drill blank loss pattern the next four intact cutters, which would have been lost had the drill test continued, were removed for evaluation. Two studs which had lost PDC drill blanks were also removed for evaluation.

The intact PDC cutters had relatively large wear flats which extended past the braze joint into the carbide stud. Considering the short duration of the test and the large amount of wear, it is doubtful that the diamond material was removed solely by an abrasive wear mechanism. Although ultrasonic testing of two intact PDC cutters showed no bulk thermal damage [6], some damage on the diamond wear flat was found using the SiC grit blast test, see Appendix A. However, the damage observed was significantly different than that observed for the hot air laboratory test; compare Figure 11(b) with Figure 12(b) in Appendix A. The rapid wear rate observed in this drilling test may have been caused in part by this localized damage. The cracks on the diamond wear flat could have been caused by frictional heating, cyclic fatigue, or impact loading.

Two observations help define the temperature of the braze joint during drilling. First, no cemented carbide plastic deformation was found on the studs which had lost PDC drill blanks, nor was any evidence found that deformed layers had spalled off. Second, a SEM examination of the failure surfaces of the two removed studs found no areas of hot shortness. It is estimated that the braze temperature during the Geysers air test was less than 1500°F, which is significantly less than the braze solidus temperature of 1645°F. It is suggested, therefore, that the origin of damage on diamond layer wear flats was cyclic fatigue and impact loading rather than thermal.

The SEM examination of the two studs also revealed three characteristic areas on each failure surface: (1) a periphery region where no bonding had occurred between the braze and the stud, on the average 23% of the bond area, (2) a ductile failure region within the braze which had a set of parallel lines remarkably similar to the ground surface finish of an unbonded cemented carbide stud, on the average 25% of the bond area, and (3) a relatively smooth region with little evidence of ductility which is typical of braze joints which had not bonded because of surface contamination, on the average 52% of the bond area.

Figure 7(a) shows a periphery region while Figure 7(b) shows a ductile area surrounded by the smooth unbonded region.



(a) (b)

Figure 7. Failure surface of studs which lost PDC drill blanks during the Geysers air test. (a) 10x (b) 200x

Two of the four intact cutters were cross sectioned perpendicular to the braze, polished and examined metallographically in the light microscope. A region of nonbonding existed along one or both braze-cemented carbide interfaces at the periphery. If the assumption is made that the cross section planes were representative, then 12% and 35% of the potential braze joint areas were lost for these two cutters due to poor periphery bonding. These results are consistent with that observed in the SEM.

Braze alloys containing manganese are susceptible to oxidation, and braze joints must be made in nonoxidizing atmospheres. The dark color of the braze around the periphery and the uniformity in depth of the nonbonding periphery region as observed in the SEM suggest that the protective atmosphere during brazing was insufficient. The braze alloy oxidation would preclude a bond between the braze and the stud around the periphery. It is possible that a higher than intended braze temperature existed which resulted in an increased oxidation depth.

Premature failure of the GE/Smith Geysers bit is attributed to two factors: (1) the lack of bonding around the periphery, most probably due to oxidation during brazing, and (2) large regions where the braze did not bond to the cemented carbide substrate of the PDC drill blanks, most probably due to contaminated surfaces. For the two studs examined these two factors reduced the load carrying capacity to 20%-30% of the normal value. Since the Geysers test occurred in a steam producing well, it can be presumed that the formation was fractured. Impact loading could easily detach one or both of these cutters, and loss of a PDC cutter would result in rapid wear of the carbide stud. Remaining cutters would be loaded nonuniformly to ever increasing magnitudes until, one by one, fourteen PDC drill blanks were lost sequentially from the outside toward the center of the bit.

Strata Bit Geysers Test

The two PDC drill blanks that had been removed with a pair of vise grips were examined in the SEM. Chemical analysis by EDS established that failures occurred within the braze or at braze-stud interfaces; no tungsten was detected. Many areas are present in Figure 8(a) where the braze was smooth, which is characteristic when no bond was formed between the braze and the stud. A higher magnification photomicrograph of the upper part of Figure 8(a) shows a well developed region of hot shortness, see Figure 8(b). Even regions showing ductile shear rupture had nodules dispersed across the surface with smaller areas where cracks had developed at grain boundaries, and this is depicted in Figure 8(c).

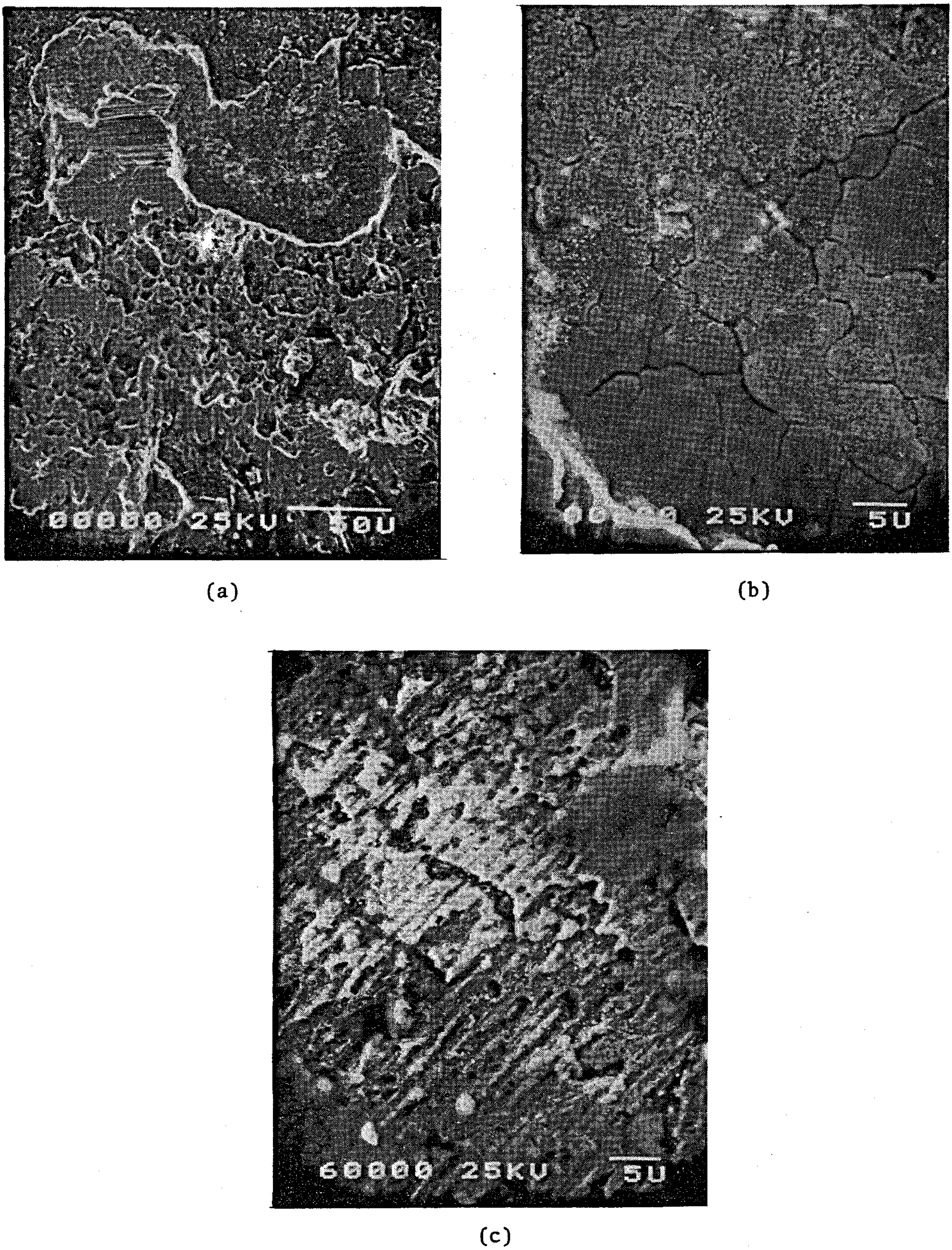
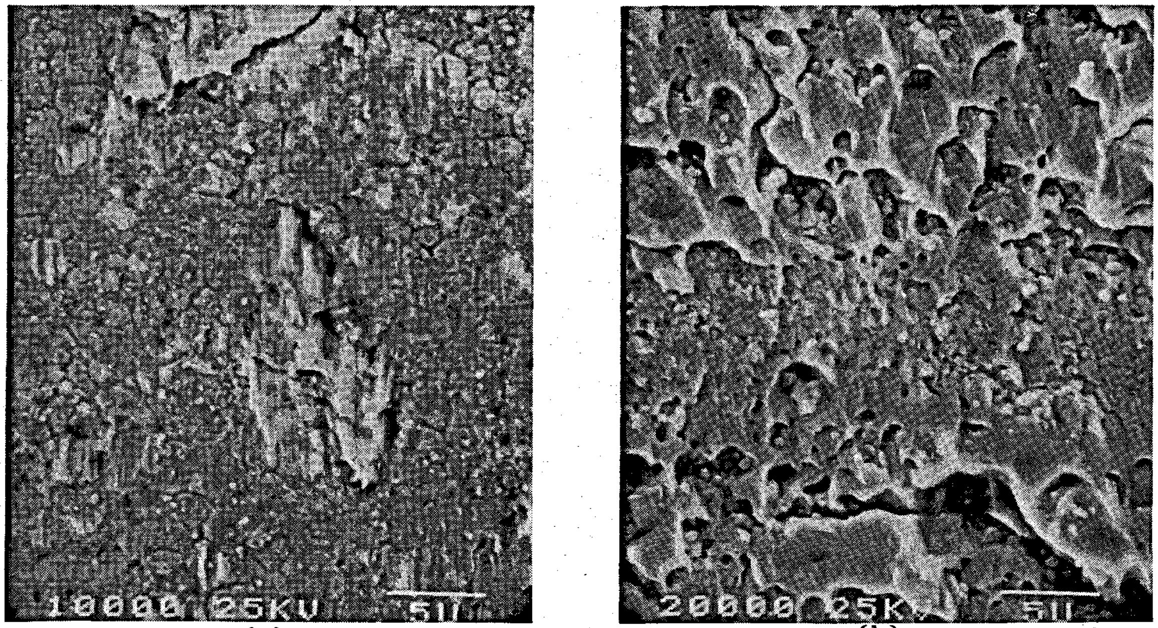


Figure 8. Failure surfaces of the PDC drill blanks removed from the Strata Bit Corp. drill bit after the mud cooled turbine test at the Geysers; (a) 400x (b) 2000x (c) 2000x

Failure was, therefore, due to hot shortness and smaller regions of defective bonding between the braze and the cemented carbide stud. These defects reduced the load capacity of PDC cutters resulting in loss of PDC drill blanks. The mud cooling fluid should have maintained the braze temperature blow levels where hot shortness would have been developed during drilling. Furthermore, small wear flats existed on PDC cutters, so frictional heating was minimal. These points suggest that hot shortness was developed during the brazing step. To support this suggestion, an evaluation of a second GE/Smith bit is included here. This bit was assembled but had not been used in a drilling test.

On the unused bit, ultrasonic testing was performed on each PDC cutter. No bad bonds were identified. Since concern existed that ultrasonic testing may not detect all possible defects, a special fixture was prepared which could be inserted individually over each PDC drill blank. The fixture distributed an applied load uniformly over the PDC drill blank loading the braze joint primarily in shear. A two pound hammer was used to impact the fixture thereby loading the braze joint. Four out of four PDC drill blanks were detached. Subsequently, a five pound sledge hammer was used on several "good" PDC cutter units without removing the PDC drill blanks.

PDC drill blanks removed in the hammer test were examined in the SEM. EDS established that all of these failures occurred within the braze or at braze-stud interfaces. No regions indicating lack of wetting of the stud by the braze were found. The failure mechanism was hot shortness which was spatially distributed throughout the braze. Two typical photomicrographs are shown in Figure 9. Hot shortness decreased the braze joint load carrying capacity to levels that PDC drill blanks were removed from the stud with a two pound hammer. The hot shortness must have developed during brazing, since the drill bit had not been tested. An improper time-temperature braze cycle can be responsible for the development of hot shortness during brazing.



(a) (b)

Figure 9. Hot shortness present on the PDC drill blanks removed from the untested GE/Smith bit.

The reader is reminded that all of the PDC cutters were tested ultrasonically before the hammer test. The supplier also 100% ultrasonically tests PDC cutters before delivery. Neither of these tests found any defects; hence, ultrasonic testing does not detect hot shortness, even when the hot shortness is extensive.

CONCLUSIONS

The PDC drill bits tested in the laboratory with hot air failed catastrophically due to hot shortness developed during testing; high temperatures were generated by frictional heating. Drilling conditions at failure help define regions where PDC drill bits using copper-manganese-cobalt brazes will not perform well.

The PDC drill bits field tested at the Geysers failed prematurely due to braze joint deficiencies. Three failure mechanisms were identified:

1. Hot shortness developed during the brazing process.
2. Nonbonding around the periphery due to oxidation of the braze during the brazing process.
3. Nonbonding either between the PDC drill blanks and the braze or the braze and the stud due to contamination prior to brazing.

No evidence was found to suggest that the braze joint failures in the field tests were caused by frictional heating.

The ultrasonic inspection technique currently used to screen the LS brazed cutter assemblies does <u>not</u> detect hot shortness. Also, it is probable that ultrasonic testing does not detect all types of nonbonding due to contamination prior to bonding, particularly if intimate contact exists across the nonbonded regions.

RECOMMENDATIONS

Hot shortness developed during brazing could be eliminated either by substituting a braze alloy with a tighter melting range or by incorporating a temperature feedback loop in the braze cycle. Important factors to consider in selecting a new braze are hot shortness tendencies, fatigue strength, impact toughness and oxidation resistance. The recommended GE braze procedure uses an induction heater power source. A temperature control feedback loop to the induction heater, utilizing for example an infrared radcometer, would give production consistency; the effects of operator error, ferromagnetic coupling variations due to shifts in cobalt content and changes in the bond joint configuration, and power supply inconsistencies would be eliminated. All of these factors can contribute to the development of hot shortness during brazing.

Oxidation related poor bonding around the PDC drill blank periphery could be improved by modification of the protective atmosphere delivery system and by temperature control. If the cover gas was introduced at two or three locations around the periphery, the atmosphere protection gas could more efficiently purge the oxygen from the braze joint volume. Temperature control would limit excessively high temperatures which enhance oxide penetration.

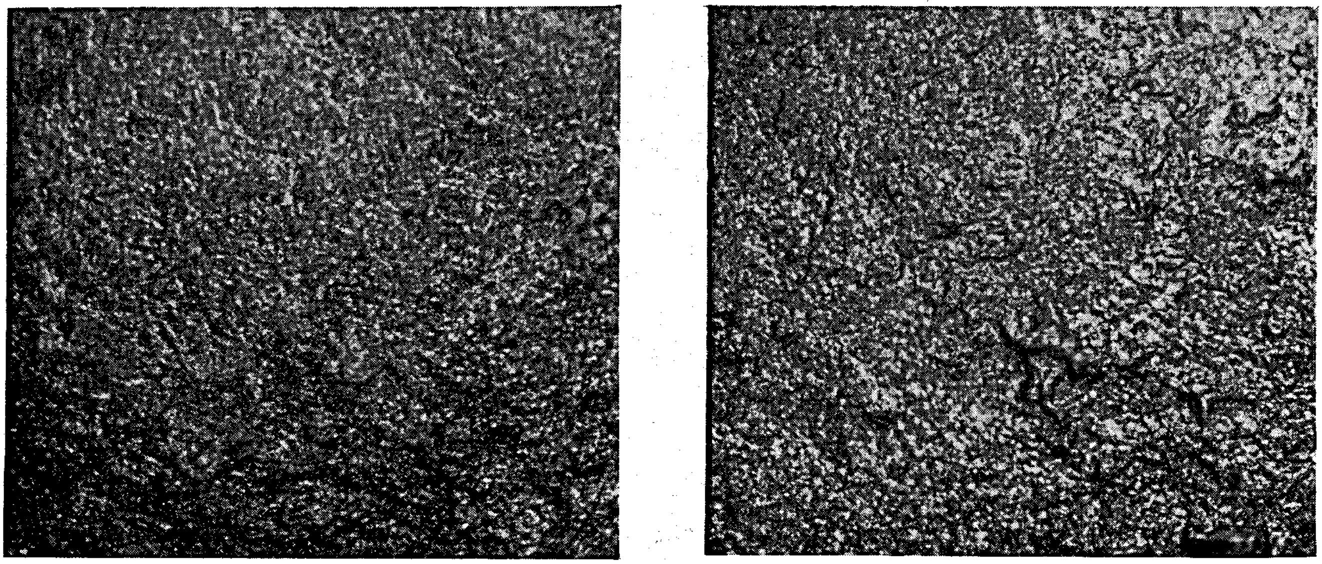
Elimination of bond defects caused by contamination prior to brazing can be accomplished by tightening the cemented carbide surface preparation, braze and assembly procedures.

APPENDIX A

Thermal Degradation Tests of Polycrystalline Diamond Layers*

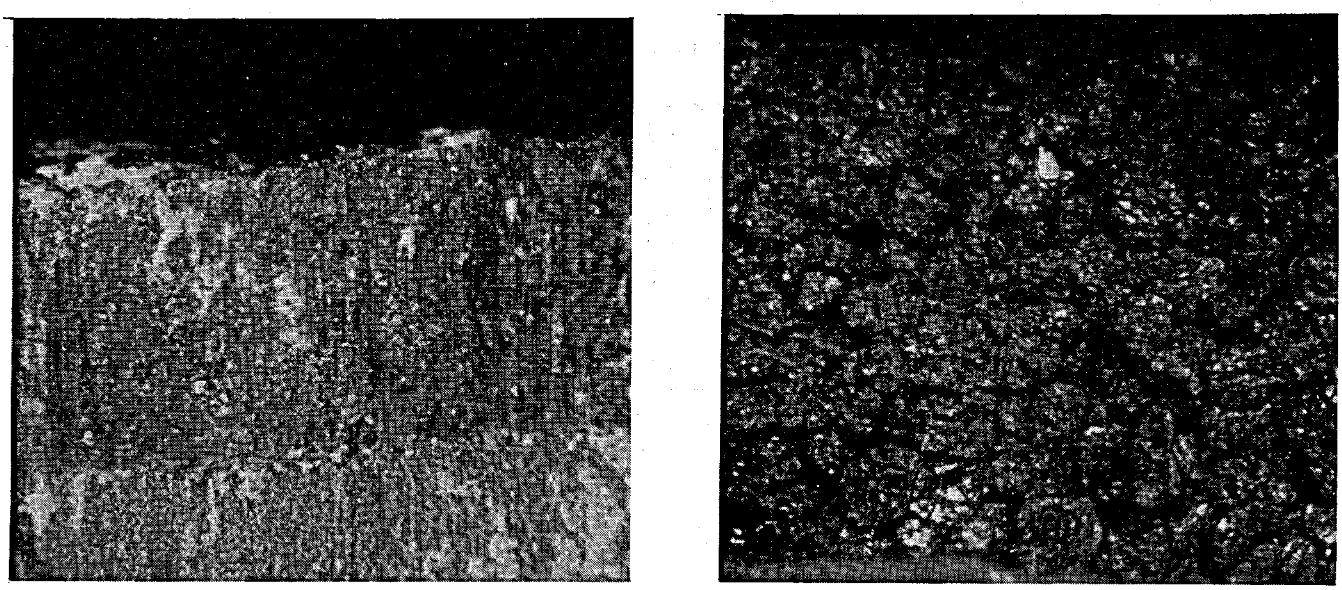
Diamond layer surface damage on the wear flats of PDC drill blanks can be detected by a SiC grit blast of up to 45 seconds with 200-230 mesh SiC. The grit blast removes tightly adhering debris and diamond material which is not well bonded to the sintered structure; little damage is produced by the SiC grit blast itself. Wear flats on selected samples from the hot air laboratory, the hot air Geysers tests, and a control were subjected to the SiC grit blast test. An 80 second grit blast had minimal effect on the control as is shown in Figure 10. A 15 second grit blast was sufficient to remove the glassy coating on the diamond wear flats of PDC drill blanks used in the hot air laboratory test, see Figure 11(b). Extensive thermal damage was observed on the diamond layer. Grain boundaries were fractured and eroded away, and diamond crystal pullout was common. A different type of damage was present on samples from the hot air Geysers test, see Figure 12(b). A 45 second grit blast revealed massive cracks and regions where diamond material was pulled out from the surface. This type of damage could have a thermal or a cyclic fatigue and impact loading origin.

*The photomicrographs in this section were provided by the GE Research and Development Center, Schenectady, New York.



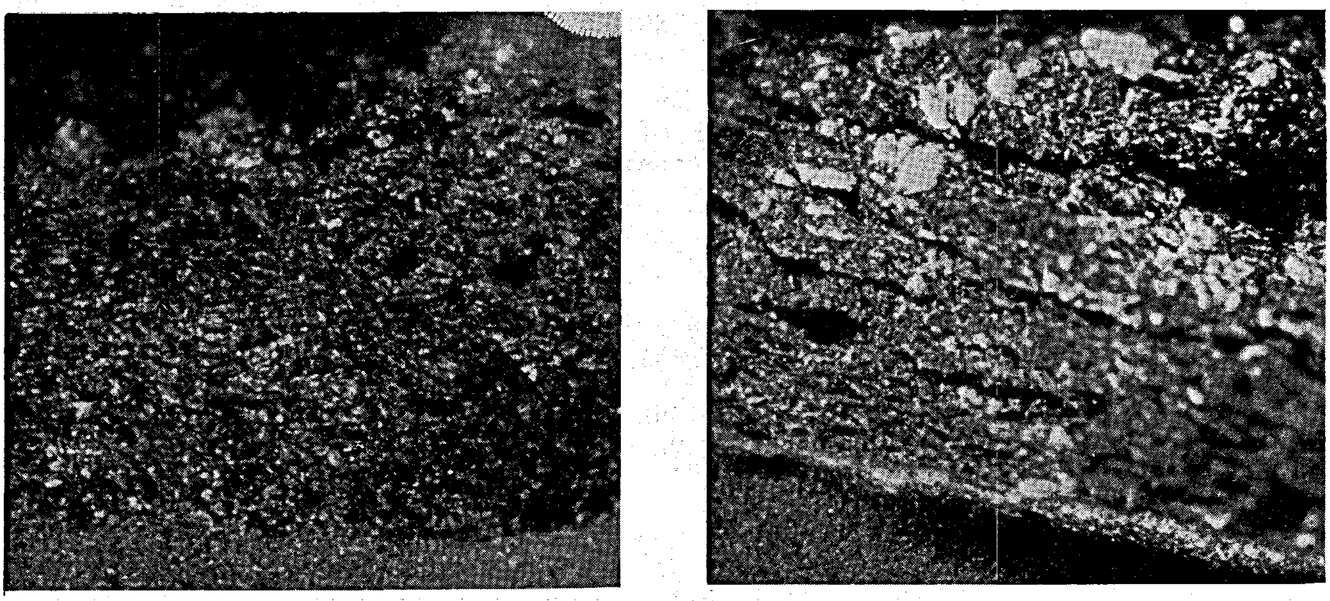
(a) (b)

Figure 10. Effect of 80 second SiC grit blast on the polycrystalline diamond layer of the control PDC drill blank; (a) before grit blast (b) after grit blast



(a) (b)

Figure 11. Effect of 15 second SiC grit blast on the polycrystalline diamond layer on the wear flat of a PDC drill blank used in hot air laboratory test; (a) before grit blast (b) after grit blast



(a) (b)

Figure 12. Effect of 45 second SiC grit blast on the polycrystalline diamond layer on the wear flat of a PDC drill blank used in the Geysers air test; (a) before grit blast (b) after grit blast

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