

April 7, 1964

H. C. BRIDWELL ETAL

3,127,945

DRAG BIT

Filed March 2, 1960

3 Sheets-Sheet 1

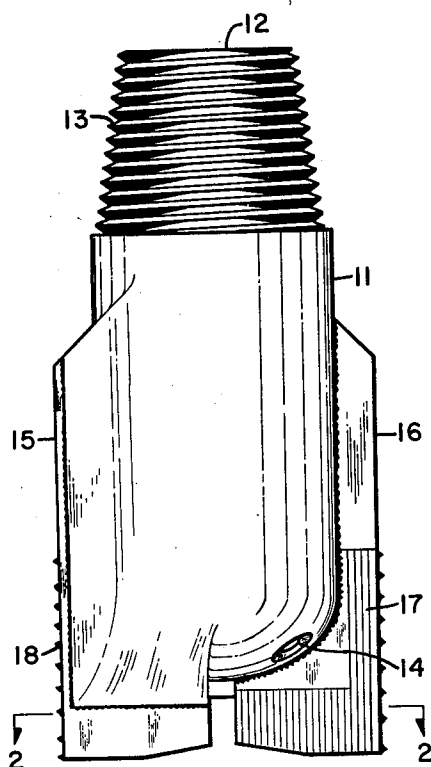


FIG. 1

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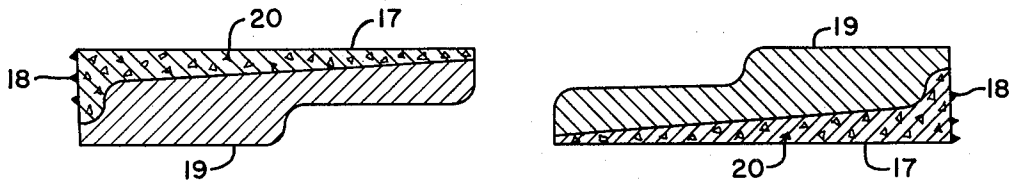
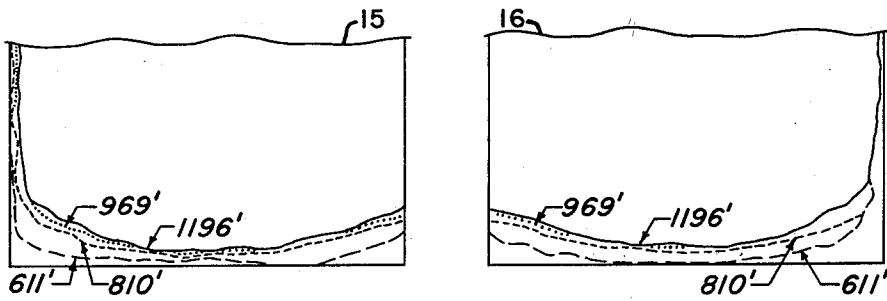
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3 Sheets-Sheet 3

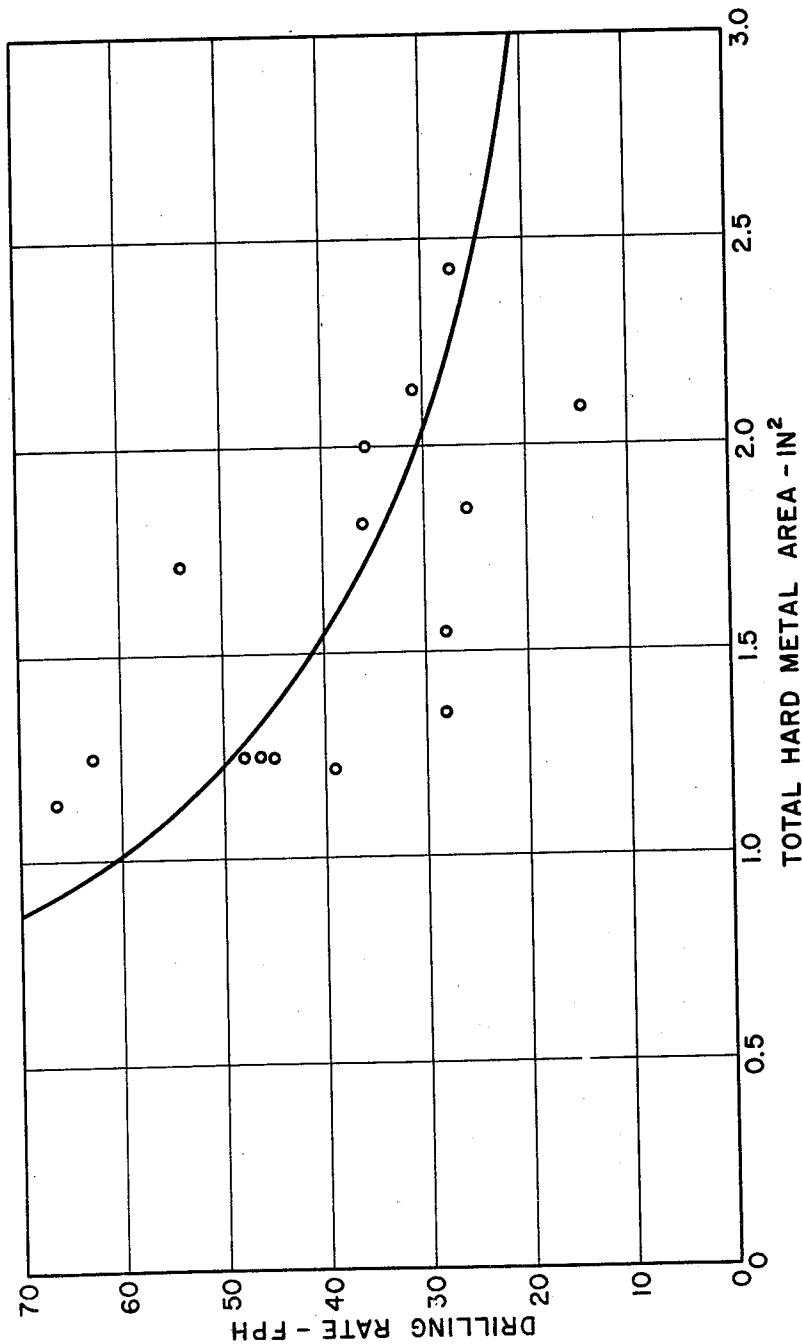


FIG. 4

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3,127,945 DRAG BIT

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5 Claims. (Cl. 175—329)

The present invention relates to bits useful for drilling oil wells, gas wells and similar boreholes in the earth and more particularly relates to an improved rotary drag bit.

Although drag bits were at one time used in virtually all rotary drilling operations carried out in the oil and gas industry, their use has greatly been restricted in recent years because of the short drilling life ordinarily obtained with such bits. The wear rate of drag bit blades, even in clays, soft shales, alluvial deposits and similar formations, is often so high that only a few hundred feet of borehole can be drilled before the bit must be replaced. To replace a rotary bit requires that the entire drill string be pulled from the borehole, dismantled section by section, and later reassembled and lowered back into the hole. Each such trip may take several hours. Because of the time and expense which must thus be expended at frequent intervals when conventional drag bits are employed, such bits have largely been replaced by roller cone-type bits except where very soft formations tend to reduce the cutting efficiency of the latter. This is true despite the fact that the initial cost of a roller cone bit may be higher than that of a conventional drag bit.

There have been many suggestions in the past as to methods for increasing the useful drilling life of rotary drag bits. The use of heat-treated alloy steel blades surfaced with hard metals is conventional but has not resulted in bits having satisfactory wear rates. Tungsten carbide, silicon carbide and similar wear-resistant insert materials, mounted either on the face of the blade or embedded longitudinally as finger inserts, have been utilized but do not extend blade life sufficiently to permit drag bits to be used economically in harder formations. In general, it has been found that improvements in blade life are usually obtained at the expense of reductions in drilling effectiveness. This route to increased blade life is obviously not an attractive one.

The present invention provides a new and improved drag bit which has considerably longer drilling life than drag bits available heretofore and at the same time permits drilling rates well in excess of those obtained with conventional bits. In accordance with the invention, it has now been found that drag bit blades having a hard, tough matrix section in which are dispersed discrete cutting particles of critical size having a hardness in excess of about 85 on the Rockwell A scale have drilling lives considerably longer than those of drag bit blades available commercially and will drill sandstone and other relatively hard strata at rates in excess of those obtained with the commercial blades. The use of drag bits provided with such blades makes possible substantial reductions in the cost of drilling boreholes. The reduced number of trips into and out of the borehole which must be made during the drilling operation, the reduced bit cost per foot of hole drilled, and the reduced time required to drill a borehole of given depth all contribute. These savings in many cases make the drag bits of the invention much more attractive from the standpoint of drilling economics than any other type of rotary bit.

The improved drilling rate and resistance to wear and abrasion of the drag bit blades of the invention can readily be explained in terms of the basic cutting mechanisms involved. Studies have indicated that particles of diamond, metal carbide, metal boride or similar material

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embedded in the matrix section of the bit blade penetrate into the formation under axially applied loads and, as the blade is rotated, remove rock chips in a manner similar in some respects to that in which chips are formed in metal cutting processes. In other words, the chip-forming mechanism is essentially one based upon shear failure of the rock. As the cutting edges of the particles become worn by mechanical attrition and thus lose their cutting ability, excessive forces build up on the particles, fractures occur within the particles, and new, sharp edges are presented to the formation. Dull particles which will neither cut the formation effectively nor fracture readily are normally torn from the matrix by mechanical abrasion. This combined fracturing of the particles and abrasion of dull particles from the matrix results in the continuous presentation of sharp cutting edges to the formation and is responsible for high drilling rates and wear resistance which is much improved in comparison to the wear resistance of blades available commercially. Critical features of the bit of the invention to be pointed out hereafter will be explained in terms of these mechanisms. It should be understood, however, that other mechanisms may also be involved and that the invention is not to be restricted to any particular explanation for the surprisingly improved results obtained in accordance therewith.

The hard particles which serve as the cutting elements in the bit of the invention may be diamond particles or particles of a variety of metallic carbides and borides having hardness values in excess of about 85 on the Rockwell A scale. Suitable metallic carbides and borides include those of tungsten, titanium, tantalum, chromium, molybdenum, niobium, vanadium and zirconium. Boron carbide may also be used. Sintered products based on certain of these materials, particularly tungsten carbides, normally contain from about 3.0% to about 6.0% by weight of iron, cobalt or nickel as a bonding agent which serves to increase the toughness of the final product and aid in the sintering process. Cobalt is particularly beneficial in this respect. Suitable carbides and borides are available from a number of commercial sources and are generally preferred for purposes of the invention because of their low cost as compared to that of diamonds. Mixed carbides, particularly alloys of the basic tungsten carbide-cobalt alloy with small additive amounts of various carbides such as tantalum carbide, titanium carbide, chromium carbide, vanadium carbide and molybdenum carbide, are also readily available commercially and may be utilized for purposes of the invention.

Tungsten carbide employed in the bits of the invention, either in the form of particles which serve as cutting elements or, as will be pointed out later, in the matrix material, will preferably be of the sintered rather than the cast type. Tungsten carbide occurs in two forms, mon tungsten carbide (WC), and tungsten sub-carbide (W_2C). Tungsten sub-carbide is extremely brittle and hence does not generally possess the shock-resistance required of the materials utilized in the bits of the invention. It also fails to maintain a satisfactory cutting edge. Cast tungsten carbide consists essentially of a mixture of WC and W_2C and therefore has some of the properties of the sub-carbide. Although the cast material may be employed for purposes of the invention, it is generally less satisfactory than the sintered product composed mainly of the mon tungsten carbide.

The metallic carbide particles employed as cutting elements in the bits of the invention are generally prepared by crushing or fracturing larger pieces of the alloy. The resulting angular particles are retained in the matrix better than smooth, rounded or spherical particles and are more effective cutting elements because of their sharp edges. The angular particles also fracture to form new

cutting edges more effectively than do particles of regular shape.

The size of the particles employed is an important factor in determining the drilling rate and wear resistance of the bit blades utilized in accordance with the invention. The particles must be small enough to prevent gross fractures and resultant rapid loss of the cutting elements and at the same time must be large enough to present a highly irregular, rather than smooth, cutting edge to the formation. This latter requirement dictates that the particles be appreciably larger than the basic grain size in the formation to be drilled.

In general, the particles employed as cutting elements in the blades of the invention should fall within the range between about 0.045 inch and about 0.250 inch, as determined by means of a screen having circular openings, and should not vary within this range more than about 0.045 to about 0.065 inch. Too wide a range in the particle size permits close packing of the particles during fabrication of the blade and results in improper binding of the particles in the matrix. The use of carbide and boride particles ranging between about 0.095 inch and about 0.155 inch has been found to result in blades having particularly outstanding drilling characteristics and wear resistance and hence particles within this size range are preferred. When diamonds are employed as the cutting elements, sizes at the lower end of the scale will normally be used because of the high cost of the larger diamond particles.

The matrix used to support the diamond, carbide or boride particles employed in the drag bit blades of the invention must be capable of securely bonding each of the individual particles in place and at the same time must be relatively tough and wear resistant. The necessary properties are attained by utilizing in the matrix a combination of a finely divided metal carbide or boride and a suitable bonding metal. Both of these constituents are important in the matrix composition and neither of them can be omitted.

Any of the metal carbides or metal borides suitable in the form of particles for use in the cutting elements of the blade may also be employed in the matrix composition. Cast or sintered tungsten carbide; titanium carbide; tantalum carbide; alloys of tungsten carbide with lesser amounts of tantalum carbide and titanium carbide; and tungsten, tantalum and titanium carbide alloys containing minor, additive amounts of chromium carbide, vanadium carbide, molybdenum carbide, niobium carbide, and zirconium carbide are preferred. The carbides and borides utilized in this manner in the matrix composition are employed in the form of fine powders, generally ranging in size from about 150 mesh to about 400 mesh, preferably from about 175 to about 325 mesh, on the Tyler scale. In order to promote the wettability of the fine carbide or boride powder by the molten bonding material during fabrication of the blade, a lesser amount of iron, nickel or cobalt is normally utilized in conjunction with the carbide or boride. It is preferred to employ from about 10 to 25 percent of the iron, nickel or cobalt and to ball mill it with the carbide or boride powder until the entire powder mixture has been thoroughly comingled and reduced to the 175 to 325 mesh size. The amount of iron, nickel or cobalt thus employed is independent of the quantity present in the carbide or boride composition itself.

The bonding agent utilized in the matrix composition comprises one or more metals melting at temperatures below about 2400° F. and having the ability to wet the diamond, carbide or boride particles when in the molten state. Higher melting metals are generally unsatisfactory because of the adverse effect of high temperatures on the diamond, carbide or boride particles during fabrication of the blades. Suitable metals for use in the matrix include copper; copper-nickel alloys containing up to about 50% nickel; copper-zinc alloys containing up to

about 25% zinc; copper-nickel-zinc alloys containing up to about 20% nickel and up to about 25% zinc; copper-silicon alloys containing up to about 3% silicon; copper-silver alloys containing up to about 80% silver; copper-beryllium alloys containing up to about 3% beryllium; copper-cadmium alloys containing up to about 18% cadmium; and similar alloys containing additive amounts, generally less than about 2% of boron, iron, phosphorous, tin and the like. It will be understood that the above metals are merely representative of those which may be included in the matrix composition and that other metals which will wet the hard particles utilized and will melt at temperatures below those injurious to the particles may be used.

In fabricating the blades of the invention, the matrix containing the hard diamond, carbide or boride particles is affixed to an alloy steel blade body. It has been found that the cross-sectional areas of the body and matrix sections of the blade must be carefully controlled in order to obtain a blade having satisfactory drilling characteristics and suitable resistance to wear and abrasion. The steel body itself must be thick enough to enable the blade to withstand the stresses established as it is rotated in contact with the formation but should be no thicker than is necessary for strength purposes. The thickness required will, of course, depend to some extent upon the length of the blade. The width of the blade obviously depends upon the diameter of the bit.

Studies have shown that the area of hard metal in contact with the bottom of the borehole during drilling, the cross-sectional area of the blade hard metal matrix sections on the bit in other words, is particularly important. It has been found that at constant bit loadings the drilling rate increases as the area of hard metal decreases. This relationship is approximated by the expression $R=K/A$, where R is the drilling rate in feet per hour, A is the hard metal cross-sectional area in square inches, and K is an empirical constant. The numerical value of K depends in part upon the characteristics of the formation being drilled and in part upon the drilling conditions. It is thus apparent that the cross-sectional area of the matrix section of the blade must be limited if acceptable drilling rates are to be obtained. It will be equally apparent, however, that sufficient hard metal area must be provided in order to give the blade the necessary resistance to wear and abrasion. Since the required matrix area varies with bit diameter, the most convenient method for expressing this is as a fraction of the cross-sectional area of the borehole. Tests have shown that in order to obtain high drilling rates and long blade life at the same time, the cross-sectional area of the total hard metal in contact with the formation at the bottom of the borehole should range between about $\frac{1}{4}$ and about $\frac{1}{8}$ of that of the borehole. The use of matrix sections having a total cross-sectional area between about $\frac{1}{18}$ and about $\frac{1}{30}$ of that of the borehole is preferred. The cross-sectional area of the matrix section of a single blade will obviously depend upon the number of blades to be used on the bit. By dividing $\frac{1}{14}$ to $\frac{1}{36}$ of the borehole cross-sectional area by the number of blades, the requisite area for each blade is obtained.

It has also been found that the cross-sectional configuration of the blade is an important factor in obtaining high drilling rates and effective resistance to wear and abrasion. It is essential that the blade wear at a substantially uniform rate across its face. If the wear rate near the inner edge of the blade is higher than that at the outer or gage edge, an unsupported section will be left at the outer edge as the drilling operation progresses and eventually the entire blade will break off. If, on the other hand, the gage edge wears appreciably faster than the inner edge, the blade will eventually assume a tapered contour and will tend to wedge in the hole, preventing further drilling and in some cases leading to a failure of the drill string above the bit. Since the velocity of the blade as it ro-

tates with respect to the formation increases from the inner edge to the gage edge, the thickness of the matrix section which imparts resistance to wear and abrasion should increase in an approximately corresponding manner. The matrix section should extend across the face of the blade in an essentially uninterrupted pattern. In general it is satisfactory to employ a matrix section which is from about $\frac{1}{16}$ of an inch to about $\frac{3}{16}$ of an inch thick at the inner edge of the blade and increases in thickness toward the gage edge at an angle from about $1^{\circ}30'$ to about 6° . The matrix section may be stepped across the face of the blade rather than increasing in thickness uniformly, in which case the steps will be such as to increase the matrix thickness across the face of the blade at an angle between about $1^{\circ}30'$ and about 6° . Because of the wear which occurs due to abrasion of the gage edge of the blade against the borehole wall, the matrix section should be much thicker at the gage edge. Preferably the matrix will extend from the leading edge over from about 50 to 75 percent or more of the gage edge, measured along the bit periphery, and will be from about $\frac{1}{4}$ of an inch to about 1 inch thick on the gage edge. Diamonds, preferably about $\frac{1}{8}$ carat in size, may be embedded in the matrix surface on the gage edge of the blade in order to further increase resistance of the blade to wear and abrasion and improve cutting efficiency at the gage.

These and other aspects of the invention can be more fully understood by referring to the following detailed descriptions of specific drag blades constructed in accordance with the invention, methods used to fabricate the blades, and tests carried out using such blades, and to the accompanying drawings, in which:

FIG. 1 illustrates a drag bit provided with blades constructed in accordance with the invention;

FIG. 2 is an enlarged cross-section view through the blades of the bit shown in FIG. 1 taken along the line 2—2;

FIG. 3 shows the contour of a set of drag bit blades such as those depicted in FIGURES 1 and 2 at intervals during a drilling operation carried out with the bit fitted with those blades; and,

FIG. 4 is a graph showing the relationship between the cross-sectional area of the matrix sections of fifteen different sets of drag bit blades and the drilling rates obtained with those blades.

Turning first to FIG. 1 of the drawing, the drag bit shown therein includes a generally cylindrical body 11 having at its upper end a shank 12 provided with threads 13 by means of which the bit may be attached to a standard drill collar or length of drill pipe. Body 11 and shank 12 contain an internal passage, not shown, through which drilling fluid may be circulated from the drill string above the bit nozzles 14 on the lower surface of the body. In lieu of a threaded shank as shown, the bit body may contain a threaded API tool joint box for attaching it to the drill string. Drilling fluid pumped downwardly through the bit is discharged from nozzles 14, only one of which is shown, into the space beneath the bit. It is conventional to use tungsten carbide or ceramic, aluminum oxide alloy for example, nozzles which can be mounted in the bit body in any of several convenient ways. Bit blades 15 and 16 are welded or otherwise mounted on the body in spaced relationship to the nozzles and extend downwardly below the body. Each blade contains a hard matrix section 17 on its face and gage edges. Diamonds 18 are embedded in the surface at the gage edge of each blade. The bottom of each blade may be tapered from an intermediate point upwardly to the inner edge of the blade as shown in FIGURE 1 in order to center the blade in the hole during the initial stages of the drilling operation. The taper angle will generally fall between about 10° and about 20° .

The construction of the blades can best be seen by referring to FIG. 2 of the drawing, which is an enlarged,

cross-section taken along the line 2—2 of FIG. 1. It will be seen from FIG. 2 that each blade includes a steel blade body 19 upon which the matrix section 17 is mounted. Any of a number of tough, high strength, shock-resistant steels may be used in the blade body, the preferred variety not being of the so-called free-machining type. Specific examples of suitable steels include those designated as AISI 3310, AISI 8620 and AISI 2517. Many others are suitable and will suggest themselves to those skilled in the art. As shown in FIG. 2, the outer section of each blade is somewhat thicker than the inner section in order to compensate for the higher stresses and faster wear near the gage edge. This cross-sectional configuration for the blade body is generally preferred but is not an essential feature of the drag bit blades of the invention.

The matrix section 17 of the blades shown in FIG. 2 is made up of an abrasion-resistant powder and a bonding material and has dispersed throughout it particles or chips of sintered tungsten carbide 20. The abrasion-resistant powder contains about 82 weight percent sintered tungsten carbide and about 18 weight percent nickel and is prepared by milling the tungsten carbide and nickel together and screening the comingled material to a 175–325 mesh size. The binding material is a cupronickel alloy containing about 75 weight percent copper and about 25 weight percent nickel. Methods for fabricating the matrix will be discussed hereafter.

The sintered tungsten carbide chips 20 dispersed throughout matrix 17 range in size from 0.098 inch to about 0.153 inch along their maximum dimension. As pointed out heretofore, the size of the particles used is critical if acceptable drilling rates and suitably low wear rates are to be obtained. The 0.098 to 0.153 inch range falls within the acceptable range of about 0.045 to about 0.250 inch and does not vary more than the 0.065 inch value specified earlier.

It can be seen that the matrix section 17 of the blades shown in FIG. 2 of the drawing is about $\frac{1}{8}$ inch thick along the inner edge of the blades and increases in thickness at an angle of about 3 degrees toward the gage edge. Along the gage edge, the matrix is about $\frac{3}{16}$ inch thick and extends from the leading edge to a point about two-thirds the distance from the leading edge to the trailing edge. The total cross-sectional area of the matrix sections of the two blades shown in FIG. 2 is about 1.5 square inches, about $\frac{1}{24}$ of the cross-sectional area of the $\frac{6}{32}$ inch borehole drilled by the bit. This matrix configuration and cross-sectional area fall within the ranges found to result in acceptably high drilling rates and suitably low wear rates.

It will be understood that the bit described in conjunction with FIGURES 1 and 2 of the drawing is a specific bit fitted with specific blades prepared in accordance with the invention and that the characteristics recited with respect thereto are not necessarily limitations applicable to all drag bits and drag bit blades falling within the scope of the invention. Blades constructed in accordance with the invention may be utilized on two-way, three-way or four-way bits, provided that the matrix section of each blade is limited so that the total hard metal presented to the formation falls within the prescribed range. The blade contour may be stepped downwardly across the blade face from the inner edge to the outer or gage edge. The blades may be utilized in conjunction with bits designed for extensible blades. These and similar modifications will be apparent to those skilled in the art.

In fabricating the blades of the invention, such as those described in the preceding paragraphs, it is preferred to utilize a casting technique. A carbon or ceramic mold containing a cavity conforming to the desired outer dimension of a finished drag bit blade is first prepared. The blade body is then machined to the proper dimensions from a block of alloy steel and placed in the mold so that space is left for the matrix section of the blade on the

face and gage edge. Diamonds utilized on the gage surface are glued or otherwise affixed to the wall of the mold in proper position. Irregular particles of tungsten carbide or the like which serve as cutting elements of the blade are screened to the proper size and cleaned in carbon tetrachloride or a similar degreasing solvent. The clean, screened particles are placed in the mold void corresponding to the face and gage edge of the blade. Finely ground cast or sintered tungsten carbide and nickel or a similar abrasion-resistant powder is poured into the mold void around the hard particles and gage diamonds. The mold is vibrated to form a dense, evenly dispersed mass. Pellets of a cupronickel alloy or similar binder are then placed in a receptacle with borax or a similar flux. The receptacle is provided with a channel communicating with the mold

over those utilized in conventional drag bits and the features of those blades can best be understood by referring to the test results shown in the following examples.

EXAMPLE I

A 6¾ inch drag bit provided with blades constructed in accordance with the invention was tested by drilling through about 1200 feet of shale and sandstone of varying characteristics in the Tulsa, Oklahoma, area. The blades used were those described in conjunction with FIGURES 1 and 2 of the drawing. The drilling was done with a Mayhew drilling rig and conventional auxiliary equipment. A commercial drilling mud was used. The rig operating conditions and results obtained are shown in the following table.

Table I

Interval	Formation	Formation Thickness, Ft.	R.p.m.	Weight on Bit, lb.	Circulation, g.p.m.	Pump Pressure, p.s.i.g.	Total Footage	Drilling Rate, ft./hr.
1-----	Sandstone-----	120	60	10,000	197	850	120	42.2
2-----	Shale-----	131	60	15,000	197	850	251	43.7
3-----	Sandstone-----	57	60	10,000	197	800	308	40.3
4-----	do-----	131	60	5,000	197	800	439	42.8
5-----	Shale-----	172	60	15,000	197	800	611	43.9
6-----	Sandstone-----	11	60	2,000-10,000	197	800	622	(¹)
7-----	do-----	40	60	10,000	197	800	662	28.9
8-----	do-----	135	60	15,000	197	800	797	48.3
9-----	Shale-----	172	60	15,000	197	800	969	50.4
10-----	Sandstone-----	53	60	10,000	197	800	1,022	47.5
11-----	do-----	134	60	15,000	197	800	1,156	51.2
12-----	Shale-----	40	60	15,000	197	800	1,196	54.6

¹ Not determined.

so that the molten binder will flow into the mold and fill the spaces between the hard particles and the finely divided powder after it has been melted. The parts of the mold are then assembled and the entire unit is placed in a furnace and heated to a temperature between about 2100° F. and about 2400° F., preferably about 2250° F. The mold is held at this temperature for a period of up to about 15 to 20 minutes. As it melts, the binder flows into the spaces in the mold and results in bonding between the blade body, the abrasion-resistant powder, and the hard cutting particles. The mold is then cooled and disassembled. The blades recovered from the mold may be heat treated in a conventional manner to alter the steel hardness and to relieve thermal stresses. Irregularities on the surface of the blade may be removed if desired. The blade thus fabricated may then be welded or otherwise mounted onto a suitable bit body or fitted into a drag bit designed for use with extensible blades.

Although the above method is the preferred process for fabricating the blades of the invention, other techniques may be used. When diamonds or boron carbide particles are employed as the cutting elements in the blade, for example, it is sometimes impractical to form the entire matrix section in one piece. A series of narrow matrix

As can be seen from the above table, the bit of the invention drilled at an average rate of about 47 feet per hour. The actual profiles of the blades at intervals during the drilling operation are shown in FIG. 3 of the drawing. Measurements made at the conclusion of the drilling operation showed that the wear at the center of each blade was less than ¼ inch. The wear index was computed and found to be 5470 feet of hole drilled per inch of blade wear. As can be seen from FIG. 3, the blades were by no means worn out and undoubtedly could have been used for further drilling.

Tests comparable to the test described above were carried out using the same type 6¾ inch bit body and a set of commercial blades purchased from a bit manufacturer. The blades were welded onto the body in the usual manner. The drilling rates obtained with these blades in formations essentially identical to those in which the blades of the invention were tested and under essentially the same operating conditions averaged about 25 feet per hour. The wear index of the commercial blades averaged about 1130 feet of hole drilled per inch of blade wear. These results are representative of those normally obtained with commercial blades. Data obtained in testing the commercial blades are shown in Table II below.

Table II

Interval	Formation	Formation Thickness, ft.	r.p.m.	Weight on Bit, lb.	Circulation, g.p.m.	Pump Pressure, p.s.i.g.	Total Footage	Drilling Rate, ft./hr.
1-----	Sandstone-----	123	60	15,000	213	950	123	28
2-----	Shale-----	177	60	15,000	213	950	300	23

pads or wafers containing the cutting particles, the abrasion-resistant material and the binder can be prepared by a casting technique such as that described above and subsequently bonded to the blade body with a high tensile strength copper base, nickel, manganese or zinc alloy. If this fabrication technique is used, the individual pads or wafers should be set as close together as possible, so that the matrix section is essentially uninterrupted across the face of the blade.

The superiority of the improved blades of the invention

EXAMPLE II

The superiority of the blades of the invention is further demonstrated by the results obtained in a field drilling operation carried out in the Galveston Bay area in Texas. An 8¾ inch drag bit provided with blades containing sintered tungsten carbide chips and having the features disclosed herein successfully drilled from the 3530 foot depth to the 5880 foot depth in a commercial well, a total of 2350 feet. This footage was 62 percent more than that normally obtained with commercial roller

cone bits at the same depth in the Galveston Bay area. The average drilling rate of the drag bit was slightly lower than that of the rock bits, 58.6 feet per hour as compared to about 70 feet per hour, but the increased bit life and lower bit cost per foot of hole drilled more than compensated for this difference. It thus appears that the drag bits of the invention, unlike conventional drag bits, are competitive with roller cone bits which, except in very soft formation, are now used in commercial drilling operations almost exclusively.

EXAMPLE III

The importance of the size of the hard particles which serve as the cutting elements in the blades of the improved bit can readily be seen by considering the results of tests of a series of blades containing particles of various sizes.

A set of blades constructed in accordance with the invention contained particles of sintered tungsten carbide ranging in size between 0.098 inch and 0.153 inch. It was found that under typical field conditions these blades permitted a drilling rate of 47 feet per hour and had a wear index of about 5470 feet per inch. A similarly constructed set of blades containing smaller particles of tungsten carbide having a maximum dimension of 0.031 inch permitted a drilling rate of only 31 feet per hour and had a wear index of 1610 feet per inch under the same conditions. This difference in drilling rate and wear index emphasizes the fact that particles below the critical size range do not present to the formation the irregular cutting edge necessary for effective drilling.

Another blade which was basically similar to the first blade but containing larger particles of the same sintered tungsten carbide was tested. The largest particles in these latter blades measured about 0.300 inch long their major axis. When the blades containing these larger particles were tested under the same conditions employed earlier, it was found that the larger particles permitted the removal of excessive amounts of tungsten carbide as the individual particles fractured during the normal process of attrition. The wear index was therefore quite low, only 422 feet per inch. Again it appears that the size of the particles is important.

Still another set of blades which contained tungsten carbide particles falling within the specified size range but varying in size to a greater extent than has been found permissible were tested. The particles in these blades ranged between about 0.04 inch and about 0.18 inch. Under drilling conditions the same as those in the earlier tests, it was found that the wide range in particle sizes resulted in an extremely poor wear index, only 282 feet per inch. This was apparently due to poor metallurgical bonding of the carbide particles caused by improper spacing of adjacent particles during fabrication of the blades. The use of particles of a more uniform size avoids this difficulty. It can thus be seen that the cutting element particles employed must not only fall within a prescribed size range but should also be of fairly uniform size.

EXAMPLE IV

The importance of utilizing a tough, shock-resistant binder in the blades of the invention is demonstrated by the wear rates obtained with two blades which differed only with respect to the binder employed. One blade contained cast tungsten carbide chips as the cutting elements and was fabricated with powdered cast tungsten and a cupronickel alloy in the matrix. The other was essentially the same except that a less shock-resistant binder consisting essentially of iron was used. The blade containing the cupronickel binder had a wear index of about 1980 feet of borehole per inch of blade wear. The second blade wore at the rate of one inch for each 282 feet of hole drilled, primarily because of premature fracturing of the matrix and resultant loss of hard metal from the face of the blade. It is thus obvious that the binder must be

tough and sufficiently shock-resistant to withstand stresses which otherwise shorten the life of the cutting particles. The binders listed heretofore have the necessary properties.

EXAMPLE V

FIGURE 4 of the drawing is a graph showing the drilling rates obtained with fifteen sets of $6\frac{3}{4}$ inch, two-bladed drag bits having blade matrix sections which varied in total cross-sectional area from about 1.125 square inches up to about 2.38 square inches. Although there is some deviation in the points obtained, it can be seen from FIGURE 4 that there is a general relationship between the total matrix area and the drilling rate. On a statistical basis this relationship can best be expressed by the equation $R=K/A$, where R is the drilling rate in feet per hour, K is a constant, and A is the cross-sectional area of the matrix in square inches. In the particular rock used in the tests and under the particular drilling conditions employed, K had a numerical value of about 62. Different values are obtained in other formations and with other drilling conditions but the same general relationship between the area and drilling rate exists. When the matrix cross-sectional area of a two-bladed $6\frac{3}{4}$ inch bit exceeds about 2.5 square inches, about $\frac{1}{4}$ of the area of the borehole, low drilling rates and very low wear rates are obtained. When the total matrix area is less than about 1.0 inch, about $\frac{1}{6}$ of the bottomhole area of the borehole, high drilling rates and very high wear rates are obtained. The use of a blade matrix section having a cross-sectional area which is from about $\frac{1}{4}$ to about $\frac{1}{6}$ of the cross-sectional area of the borehole, divided by the number of blades on the bit, represents the best overall compromise between drilling rate and wear rate and gives much better over-all blade performance than can otherwise be obtained.

EXAMPLE VI

The effects of small changes in the configuration of the matrix section of drag bit blades upon blade wear and drilling rate can be seen by comparing the performance of two blades constructed of identical materials but differing in that in one blade the matrix section was tapered across the face of the blade continuously in the manner described heretofore, while in the other case the matrix section was interrupted at several points across the face of the blade. Aside from this difference, both blades had essentially the same configuration. Drilling tests showed that the blade provided with a continuous matrix section had an acceptable contour after drilling 1239 feet in a sandstone formation and had a relatively high wear index, 1980 feet of hole drilled per inch of blade wear. The blade having an interrupted matrix section, on the other hand, developed an unacceptable contour after drilling only 209 feet in the sandstone and had an unacceptably low wear index of 324 feet of hole drilled per inch of blade wear. The small change in the blade configuration resulted in a six-fold change in the wear rate.

Similarly, two blades which were essentially identical except for the fact that one was provided with a hard surface on the gage edge that tapered back toward the trailing edge as in the blades of the invention and the other lacked such a surface on the gage edge were tested. It was found that the drilling rates of the two blades were substantially the same but that the first blade greatly outlasted the second, which failed at the gage edge and drilled an undergage hole. Again a very small change in blade configuration or geometry had a profound effect upon blade life.

What is claimed is:

1. A rotary drag bit comprising a bit body and a plurality of blades depending from said body, each of said blades having a face and gage edge formed from a matrix within which are bonded cutting particles between about 0.045 and about 0.250 inch in size having a Rock-

well A hardness in excess of about 85, said matrix comprising hard abrasion-resistant powder granules between about 150 and about 400 mesh in size interspersed within a bonding metal having a melting point below about 2400° F. and in the molten state having the ability to wet said cutting particles and powder granules, the thickness of said matrix decreasing across the face of each blade from the gage edge to the inner edge, and the total matrix cross-sectional area on the bottoms of said blades ranging between about $\frac{1}{44}$ and about $\frac{1}{36}$ of the area swept by said blades as said bit is rotated.

2. A bit as defined by claim 1 wherein said cutting particles are particles of cemented tungsten carbide.

3. A bit as defined by claim 1 including diamonds embedded in the gage edges of said blades.

4. A rotary drag bit comprising a bit body and a plurality of blades depending from said body, each of said blades including an elongated steel member to the face and gage edge of which is metallurgically bonded a matrix containing particles of cemented tungsten carbide between about 0.045 and about 0.250 inch in size, said matrix comprising tungsten carbide powder granules be-

tween about 175 and about 325 mesh in size bonded together with a cupronickel alloy having a melting point below about 2400° F. and in the molten state having the ability to wet said cutting particles and powder granules, the thickness of said matrix on the face of each blade increasing from the inner edge to the gage edge, and the total exposed matrix area on the bottoms of said blades ranging between about $\frac{1}{18}$ and about $\frac{1}{24}$ of the area swept by said blades as said bit is rotated.

5. A bit as defined by claim 4 wherein said carbide particles range from about 0.095 to about 0.155 inch in size.

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