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A CRITICAL REVIEW OF FACTORS INFLUENCING THE WEAR OF THERMALLY STABLE DIAMOND (TSD) ROCK DRILLING BITS

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ABSTRACT: In rock drilling, bit wear is a major factor in determining bit life, the cost of drilling and may significantly influence the drilling method selected for given rock type. Effective control of bit wear can yield significant cost savings. Prediction of cuttability or drillability requires an understanding of the cutting action and the mode of wear and their interaction with the rock properties- Wear type and degree, rate of penetration and life of thermally stable diamond (TSD) bits depends on many complex and interrelated factors. However the important factors in predicting wear rates which are considered in this paper are bit design, bit operating parameters and the characteristics of the penetrated rock under both laboratory and field conditions. The most important bit design characteristics are cutter size, shape orientation, density, profile and hydraulics All these factors are interrelated and require optimisation for the formation properties, the operating parameters of the drilling machine, fluid properties and flow characteristics. The operating parameters include weight on bit, penetration rate, rotational speed, torque, specific energy and die distance drilled. No single rock property indicator gives a satisfactory prediction of wear rates, the determination of the most important properties for a given rock and their effect on wear are discussed. Wear of TSD bits can take many forms, however the most common mechanism during drilling is abrasion Impact loading and accumulated thermal fatigue also contribute to the wear of bits Optimisation of bit design and operating parameters can lead to increased drilling rate, prolonged bit life and reduced drilling cost

1. INTRODUCTION

Wear may be defined as the removal of material from solid surfaces as a result of relative sliding motion at the contact surface Wear is inevitable phenomena m almost all the machining operations and is more significant in grinding, cutting and drilling operations It has serious deteriorating effect, because it causes a component to become totally ineffective or susceptible to catastrophic failure Further, it results in continuous depreciation of the tool, a condition which reduces drastically its effcclivc Weat may be controlled by the type and the properties of the interacting materials, the operating conditions and the type of sliding interaction

Drilling rate and bit life are two factors thai significantly affect the drilling cost per meter, which ıs laıgıhle measurement of drilling bit performance For instance, an increase or 100 % m drilling late oı bit life may l educe drilling cost by SO % or 11 % respectively (Striegler, 1979) Therefore, any parameler that can be modified to increase drilling rate oi bit life will improve drilling performance further and thus reduce drilling cosl

Although potycrystalhne diamond compact (l'HO have existed for more than 40 years, the material and its applications are still being developed. Thus, earlier PDC applications and bit design generally experienced poor and uneconomical results. Real advances in drilling efficiency were achieved in the early 1980s Since then. PDC bits have been economically employed for sort, medium strength and abrasive formations in oil field and mining applications They achieve high tares of pencil alum (ROP) while maintaining bit life However they \M-.U out rapidly when drilling haul rocks due to ihciiniil limitations llinmally stable diamond ('I SI)) \»'-K- introduced ovei Jen yeais ago and have cMemln! \ln performance advantages of V\>Ç mltui.s lu b;iui formations

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FSD compacts are produced either as composites in which the diamonds have been reaction-bonded with silicon to form a compact oi diamond with silicon carbide or as diamond polycrystals from which the cobalt catal>st has been leached bv acid etching The former is known Syndax marketed by De Beers while the latter is known Geosel produced by General Electric Co Both materials have been used as the cutting elements in rock dulling Results of field trials lor Geoset bits have been reported by McGehee et al (1986) and Weaver and Bunch (1987) while tests with Syndax have been discussed by Tomlinson et al (198S) and Tomlmson and Clark (1992) Some observation on the wear of the compacts under field conditions have been reported by Liu and Cooper (1992), Single cutter tests have been made by Cohen et al (1994) and Cooper et al (1994)

Recently the performance of thermally stable Syndax3 pin and hybrid core bits and their comparison with impregnated diamond core bits wear characteristics and mechanism, performance prediction using multi-variable analysis influence of rock characteristics, analysis of drilling detritus and its effects on the performance of these bits have been examined for a wide range of rock types by Ersoy and Waller (1994, 1995 a, b c d e f 1996, 1997 respecttevly) There is no substantial and collective wear review of TSD bits or cutters The objective of this paper is to provide a critical and comprehensive review of the effects of bit design operating parameters and *penetrated* rock characteristics *on* 1 SD wear performance based on both laboratory and held results

2 fHE MANUFACTURE AND PROPER IJES OF ISDB1TS

fSD material is a solid unbacked pol y crystalline man made diamond product which is thermally skiblc lo 1200 °C in a reducing aimosphu c (lomhnson and Clark 1992) The TSD bit crown consists of two components matux and cutler In conventional PDC bits, matrix is mainly made up Irom tungsten carbide-cobalt (WC-Co) Many cobalt based PDC products progressively degrade when heated to a temperature of 750°C due to the presence of a residual solvent/catalyst There was no cobalt used in the TSD bits Instead a ceramic (mainly silicon carbide) secondary phase is used which is chemically inert and has a similar coefficient of thermal expansion to that of diamond In addition there is no substiate to introduce problems of differential thermal expansion The matrix also contains small amounts of Cu Ni /n le and Mn The cutting material is made ot polycrvslallme diamonds m the torm of a icctangle triangle pentahedron hexahedron of \anous mm section TSD bus are manufactured bv the infiltration route using the same techniques as for other PDC products Shallow holes are dn'leJ into the graphite base plate m the selected pattern setting and the cutter pins simply gfued into position vertically Several pins are usually positioned for gauge maintenance reinforced by additional carbide wear strips and natural diamond kicker stones The number of cutter pins used m a bit and pattern setting design will depend on the formation for which it is intended From the drilling trials it has been experienced that a TSD core bit that contains fewer pins should be used for hard rock drilling, and a bit which contains more pins *is* used for soft and abrasive rock drilling (Ersoy and Waller 1995 d)

Property	Al_2O_3	Al_2O_3 + TiC	Sialon	WC (K10)	TSD	Diamond
Density (g/cm^3)	3 91	4 28	3 20	4 70	3 43	3 52
Compressive strength (GPa)	4 00	4 50	3 50	4 50	4 74	8 68
Fracture toughness (MPa m$^{0.5}$)	2 33	3 31	5 0	10 8	6 89	3 4
Knoop Hardness (GPa)	16	17	13	13	50	57-104
Young s modulus (GPa)	340	370	300	620	925	1141
Modulus of rigidity (GPa)	153	160	117	258	426	533
Bulk modulus (GPa)	243	232	227	375	372	442
Poisson ratc	0 24	022	0 28	0 22	0 086	0 070
Thermal expansion coef (10^{-6} K)	8 5	7 8	3 2	5 4	3 8	1 5 4 8
Thermal conduct (W m^{-1} K^{-1})	25	35	20-25	100	120	500 2000
Wear coefficient	0 76	0 92	0 91	0 79	2 99	2 14-5 49
Thermal shock resistance	0 60	0 62	3 17	10 2	7 44	24 5

A wide lange oi properties of TSD and other hard materials are given in I able 1 I wo of the most important criteria in the evaluation of a new material in drilling arc wcai resistance and fiaclure toughness The two properties are diametrically opposed and often a compromise must be struck for a particular application (Tohnson et al, 198S) From the Table 1, it can be seen that TSD has a fracture toughness far higher than any of the pnncipal ceramics or single crystal diamond Another significant parameter is resistance to thermal shock which has particular relevance m drilling applications A low thermal expansion coefficient, a high resistance to crack propagation a high thermal conductivity and a low modulus of elasticity all contribute to this

3 WEARCHA.RACIbRIS'IICS

The type and degree of wear depends on many complex factors However the principal factors which need to be considered in predicting wear rates are the bit designs the bit operating parameters and the characteristics of the penetrated rock in both laboratory and field conditions Different rock types produce very different wear rates according to the nature of the interaction between the bit and rock

3 1 The Effects of Bit Design

The design parameters of TSD bits (such as cutter orientation cutter density cutter si/e and shape) have considerable effects on TSD bits life which can be greatly enhanced by optimising these variables Various cutter sizes and shapes are given in Table 2 and Figure I The effects of the design variables on TSD bits wear are summarised in the following

Figure 2 shows wear of flat sel and shaip set TSD cutters The bits had been run on high speed down-hole motors to drill directional wells mostly in limestone (Liu and Cooper 1992) I he percentage of fractures for that flat set TSD cutter is higher than that ol the shaip set TSD cutters However the percentage ot polished cutters for liai set is less than sharp set When verv. hard strata or sinngers were encountered most of the cutting elements in the contact area were chipped which resulted in poor cutting action However the matrix ot the bil was not worn II the diamond is too friable it wears faster ıhan the matrix material and most of the Weight on bit (WOB) ıs supported by the matrix and the bit can no longei penetrate the rock This is known as a polished hit condition (Ersov and Waller, 1995d) Conversely il the matrix material is too soft ihe diamonds arc inadequately supported and lail before completing then effective dnllmu, hie Therefore the matrix material musi weai at the same rate as the diamond in order to lacihtait constant dîiuuıl drilling A relalivelv soft matrix should be used tor hard rock drilling This can prolong the life of a bit by permitting erosion around the each pin element thus improving its protrusion This will result m decreasing wear and increasing penetration rate

Table 2 Product of TSD inserts (after Anon 1986)

Product series	Product no	W (mm)	H (mm)	T (mm)	S (mm)
	L222	2 5	2 5	2 5	
Rectangle	L333	3 0	3 0	3 0	-
	L444	4 0	4 0	4 0	-
	L555	5 0	5 0	5 0	-
Triangle	T42-60	4 0	-	2 5	-
	T43-60	4 5	-	3 0	
Pentahedron	P652	6 0	5 2	2 5	-
	P653	6 0	5 7	3 0	-
Hexahedron	H542	5 0	4 5	2 5	2 5
	H553	5 0	5 0	3 0	2 5

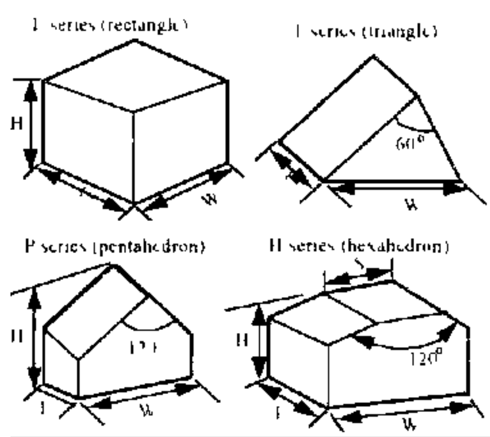


Figure 1 Dimensions and shapes oi TSD inserts (after Anon 1986)

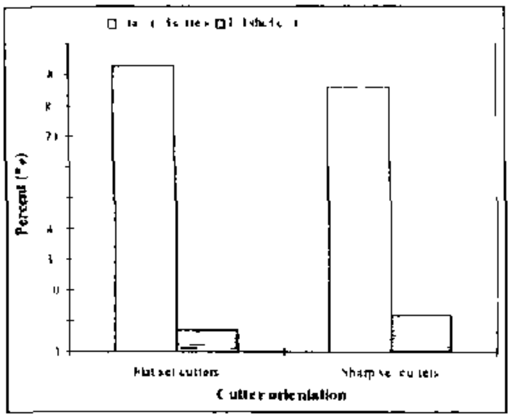
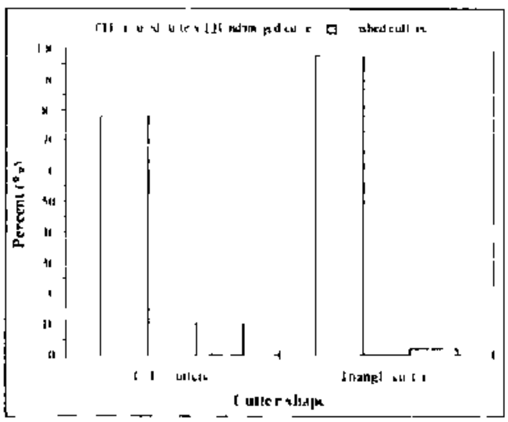


Figure 2 Effect of cutter orientation on the bil wear {after Liu and Cooper, 1992)

Shape effect on *I*SD bil wear is shown in Tigure 3 There is a great tendency for tnanglular TSD to fait Liu and Cooper (1992) indicated that this may be partly due to the fact that tnanglular cutters are relatively thin in the direction of cul, and that the bending stresses induced by the cutting action may have been sufficient to break their points off In contrast a sharp set cube is rather thicker in the direction of cut (3 mm versus 2 mm) and the angle at the apex is 90 degrees rather than 60

The number of cullers (cutter density) used in a TSD bit has a considerable effect on bit life as shown in



I igurc 3 I ffcct of cuttci shape on the bit wear (I iu and (oopci 199?)

Figure 4 (oliui (**1** il IW1) **I** he hi>ht st 1 hits Miflcrtd dm in ı\uv»ı\ı uıiiu biL<ikifi>c *(75 %)* whkli i ise d iK>nf iiiUm it linn nl Ilı hit (nn <.t\ui.iUI\ lU k 1 sluwnd llwl >i UtjiL lumiUci ul

cutters is desirable on TSD bits

Cutter size for TSD bit also influences its life, as shown in Figure 4 The most significant effect was the total absence of broken cutters with large L5S5 ISDs L^s cutters are 5 mm cubes, whereas L333 cutters are 3 mm triangles

As a result the design characteristics showed that optimised 1 SD bits utilise a large number of cutters, large size cutters and cutters with sharp point oriented downward

3 2 The Effects of Operating Parameters

The relationship of the bit operating parameters with the bit wear is given in Figure 5 Under conditions m which thermally accelerated wear does not occur the only wearing mechanism occurring is abrasive wear The abrasive wear volume is linearly proportional to the penetrating force (WOB) and therefore also to torque This implies that a WOB/torque combination will produce the least amount of wear at an economical penetration rate (Figure 5) The determination of the optimum point for the bit parameters is dependent on what the borehole is required for In many cases, the required optimum parameters will conflict with each other for example core recovery and maximum penetration rate However in most cases the predominant criteria are to produce the hole as cost effectively as possible

Cooper et al (1994) reported that the wear rale of single TSD cube cutler decreased with inue.tsing culling depth in sandslone as shown in Fıguıe 6 However Ersoy and Waller (199<ki 1996) have shown thai weight and height looses ol Syndizi I SD pin and hybrid coic bits in sandstone per meter distance drilled increased draslically with an increase of ihe ROP and torque 1 he bit weighl loss pu meler distance drilled for a wide range nl roek types was found in decrease wilh an ıncreası of the rotational spied (I isoy and Waller I99*id) I his dccitast ol wendil loss tan he allnbuled to the easier displacement of the drilling detritus with high lotalmnal speed Howevei compaied with ROP the effect of tr'e rotational speed on the wear of the bits was small

I iguit 7 shows lulling (nue \fisus distance eut over merimcnts of 88 m ((oupct el al 1994) I itlk (hdiigt oemiiid in Ihı InslS'Sm Influwini (Ins I lie milt! haeUiicd and sum (h< iiillu point was no Initt-ei piojK fmj fmwiul Ilıt dipflt nl ml tiuiuiHd forces were reduced Beyond 616m both the cutter forces and temperature were much higher than previously probably due to further cumulative damage to the bit (Liu and Cooper 1992)

Î1 I he Lffects of Rock Characteristics

Over 80% ol the earths crust is composed of hard ami potentially abusive minerals such as silica (SiO;) alumina (AI^O-^) and hematite (1-020!) It is not suipnsing thcreiore to find that the principal mechanism by which rotary drill bits are worn is ıbıasıon

Ai. investigation of the effects of textural mini ^logical, mechanical, and intact properties of a wide range rock types on the wear performance of TSD, Syndax3 product pin and hybrid core bits have recently been reported by Ersoy and Waller (i°95a,b,cd,e,f) These tests were conducted *on a* fully instrumented laboratory drilling rig at different rotational speeds and over a range of WOB tor various rock types The following conclusions were drawn

The wear rate of the bits was only marginally effected by the grain size of the rocks Below 0 4 mm, there is little influence and a small effect was noted between 0 4 and 0 7 mm gram size

A graph of grain shape against the wear rate for the drill bits is given in Figure 8 The values of grain shape range between close to 0, for very elongated or angular particles, and I for a perfect circle Oram shape is also known as form factor or cnculanty shape factor The results from tht grain shape of the rocks show that granite is most angular followed by dionte limestone (particularly elongated particles) sandstone and finally siltstone Most of the siltstonc panicles are rounded and scmı-rounded Angulaı elongated and lough panicles produce a lowu drilling rale and a highei wear lak I han rounded pdiiKİcs Tin tii'uu mdieau,s that a dcucasc in gram slupı (ınucası m <in»ulanlyj increases wear rale ol llu bus iM,i|>l loi ImifSlOlH JIHI ID sonn LXlcn sandslonc I lieu weu no haul and abıasıvc miner iK in ıhı lıııcslonc which cnihi lui wholly >l soil 1 in ı i.ili itt ti\ iials was lnghl\ pnmus <nu! *v.,i* wt it \\ hoiulul SaiulsloiK lidtl veiy In h ılua poto l\ ml was wcaklv bonded v'oNsiqutnlly il a lock loıl.ım*, UP c angular par lu les or crysl ds wlm li ne h ml uu! »liongly bonded the lock will pmduic huh wui and low ROI'

Silicate minerals are known to be more abrasive than other minerals The quartz content of the rocks alone do not account tor wear i ate of the bits However an increase in silica content of the rocks increases the wear rate of the bits

An increase in strength of rocks increases wear rate of the bus, as shown in Figure 9 Increasing abrasıvıty and hardness indices also increases the wear rate of the bits

4 THE WEAR MECHANISM OF THE TSD BIT S

Both laboratory rock cutting test and field operation for wear and failure mechanism of PDC bits have been carried out by Lin et al (1992) Wear of TSD culling elements have been investigated for a laboratory drilling (Ersoy and Waller, 1995d) and for field bits (I iu and Cooper, 1992) In TSD drilling, wear may be defined as any degradation, macroscopic or microscopic that reduces bit life by the removal or fracture of material at the cutter suiface According to the above ISD bit wear may be based on four components abrasion impact shock and fatigue impact loading and thermal shock (temperature) Firstly, abrasive wear is steady slate wear that is normally associated with the development of uniform wear flats and the gradua! degradation of rate of penetration over the bu life It is a function of the formation properties, the force applied to the cutter cutter temperature cutter velocity and cutter properties Soft plastic rocks tend to wear a flat at an angle with respect to tht rock surface which keeps a smaller aiea in contai (with the rock and the cutter in a sharper condition I laid brittle locks and conditions undei which cutlei impact loading occurs tend to wear [he flat parallü lo the lock surface leading to a Uryei aiea in contact with [he rock and higher cutting forces Secondly Impact shock under high impact lorces is caused by residual slicss whereas impact fatigue ıs a rcsnlı ol muhanical fatigue Uunng normal drilling operations llu residual slress left after the high pressure and Im h ttıipeıauıc process can cause delamination when the cutlei is subjected to high impact foices

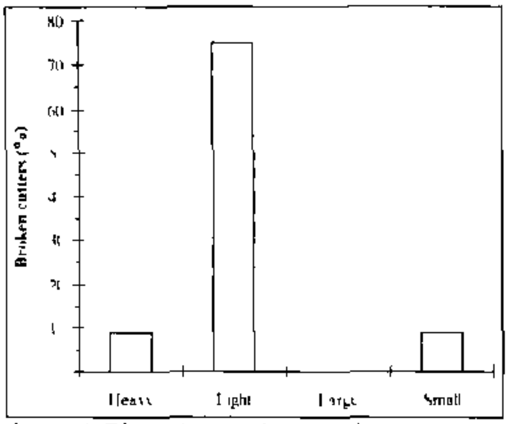


Figure 4 Effect of cutter density and cutter size on the bit wear (after Cohen et al 1993)

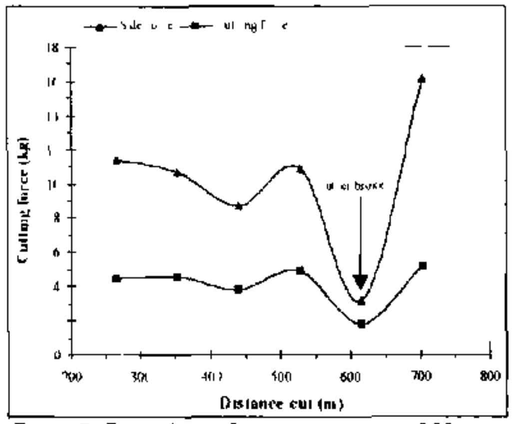


Figure 7 Cutter forces for successive cuts of 88 m in Nugget sandstone (after Cooper et al 1994)

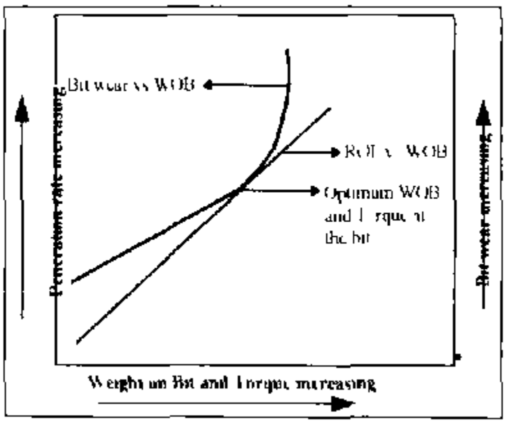
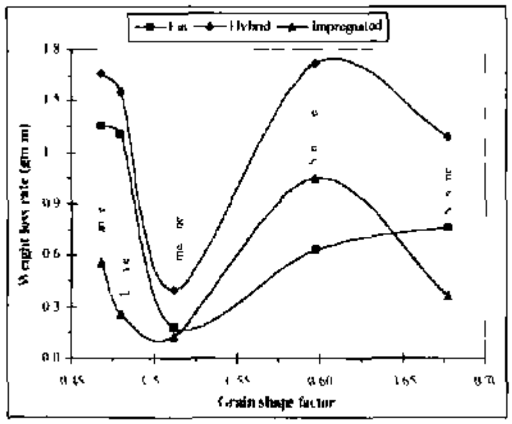


Figure ^ Relationship of the bit operating parameters with tliL bit wear (after Lrso> and Waller1995d)



hgure 8 Graph of weight loss rale agarnst giain shape factor (after hrsoy and Waller 1995d)

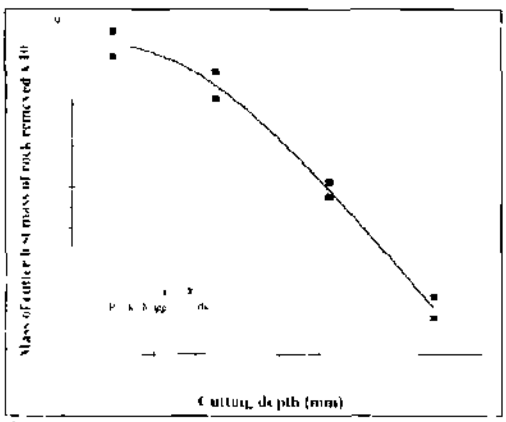


Figure 6 The ratio of cutter mass worn away to the mass of rock cut versus cutting depth (after Cooper et al 1994)

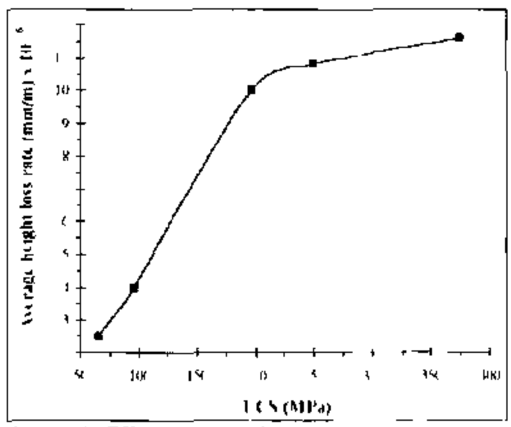


Figure 9 Effect of uniaxial compressive strength on the wear rate of Syndax ... bit (... Waller 1993)

Thirdly it is assumed ...

subjected to impact loading with the generation oi shock waves travelling through internal inclusions or surface pits of the diamond Fourthl\ temperature increases because ot fnctıonal heating of the cutter which directly influences the abrasion resistance and eventually structure of the cutter grams TSD bits have high thermal stability up to I200°C therefore temperature may not be considered as critical for the failure of the bits However Cumulative damage may result in Iracturc of the TSD cutler which ma> grow at least in part b> thermal fatigue due to repeated heating of the cutter b\ sliding over the rock followed bv quenching from the drilling mud as the bit lifts awav from the rock surface (Liu and Cooper 1992)

5 CONCLUSIONS

Optimising TSD bu geometry and design characteristics can greatly increase bit hie The designs depends on formation properties operating parameters oi the drilling machine fluid properties and types and flow hole size etc Large leitangular blocks and cubes set with a sharp point down drill taster with iess breakage than smaller race or flat set cutters

Wear rates of TSD bits are sigmlicantK effected bv the drilling sanables such as WOB RPM torque and Sh The wear rates increased drastically with an increase of WOB which also increased HOP and torque ROP (or WOB) ıs one of the most important factors influencing the wear or the bits High RPM is desirable with no adverse effects in terms of the bit wear However the (lushing mechanism must be efficient enough to lemou the e\tta detritus eflectivck to avoid inercascd bit m<un\ wcai at high speeds

Dnllabihty or cuttabihty of locks cannot be defined in an absolute manner by a single index or measured by a single lest The resistance of roek lo dulling depend-, to larye extent upon the means used for ile-.iruction Thus a wide range of eompositional mineralogical stiength and intael eharaclerisries ot the rocks should be described and quanlilali\eh presented

Wear ol TSD bits can take many loi ins bul ıhe most common wear mechanism operating on TSD bits during rock drilling is abrasion Impact loadinu. and thermal fatigue (probably due to aceumul.ucd damage) also contribute to the wear of the hits

Volumetric wear due to abrasion is proportional to the WOB and sliding distance al a particular rotational speed This phenomenon is only valid in the absence of thermal effects This wear occurs on a microscopic level through a process of impact load and shock and impact fatigue on the individual diamond grams The rate at which abrasion occuis is dependent upon the hardness differential between cutter and ioek

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