AN EXPERIMENTAL INVESTIGATION OF THE CUTTING FORCES AND WEAR AREA OF A SINGLE DIAMOND

by

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SYMBOLS USED

a	Radius of Diamond
h_w	Depth of Cut
h_{wd}	Depth of Diamond Wear
X	Axial Cutting Force
Y	Tangential Cutting Force
Z	Normal Cutting Force
R_{eq}	Radius of Wear Area (Planimeter)
R^*	Radius of Wear Area (Profile)
A_1	Wear Area (Planimeter)
A_2	Wear Area (Profile)
λ_w	Diamond Wear Angle

CHAPTER I

INTRODUCTION

The use of diamonds as a cutting tool material has a long history. They have long been used in bits by the mining and oil industry for drilling and coring rock formations that are so hard that they cannot be economically drilled or cored by any other means.

Often the costs involved are high. For example, down-time on an offshore drilling rig can cost as much as $1200 per hour and a large diamond drill bit may cost as much as $20,000. With costs like this, even a small improvement in design and operation can result in large savings.

The use of diamonds has been rather limited due to the expense of natural diamonds. Only small crystals (suitable for abrasive tools only) have been capable of being produced by synthesis.[1] Thus, it is still necessary to use natural diamonds in some cutting tools, especially oil well drill bits. In general, the cost of diamonds (either natural or synthetic) is high and the supply somewhat limited. Therefore, it is important to learn more about the basic cutting action of diamond tools so that they may be designed and operated more efficiently.

Industry has acquired a certain level of experience in the design of diamond tools, but this has been based mainly on trial and error. Appl, et. al. [1], has developed a theory of diamond cutting action;

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[1]By altering the distance between atoms of a substance when it is under severe compression leads to significant changes in its properties. By using a polymorphic transformation of the crystal structure, the new properties are maintained.

but there is insufficient experimental work to verify the theory. Most previous experimental work deals primarily with metal cutting i.e., Loladze and Bokachava [4] and Keen and Grogan [3].

Reese [6] determined experimentally the cutting forces for a single spherical diamond while cutting Indiana Limestone. Limestone is not very abrasive, and so wear of the diamond was not a factor in these tests. In many applications, however, the life and hence the cutting cost is critically dependent on the wear of the diamonds during operation. Thus, it is important to learn more about the wear of diamonds during cutting.

Most industrial tools consist of approximately spherical shaped diamonds held in a metal matrix. Fig.'s 1 and 2 show typical diamond tools. The diamonds usually protrude from the surface and are arranged in some pattern. The cutting action thus depends on the total action of all the individual diamonds. For this reason, a single-point diamond tool was selected to determine the effect of diamond wear on the cutting forces. The cutting action of a worn single-point diamond is shown in Fig. 3.

Recent work by Keen and Grogan [3] has shown that the diamond life or amount of wear is affected considerably by the orientation of the diamond. This work has shown that when the tools were oriented so that the 111 or 110 planes were close to the top face, wear resistance was increased. A check with Sidley Diamond Tool Company, the manufacturer of the tools used, revealed that the 110 plane was oriented toward the top face so this factor was not considered.

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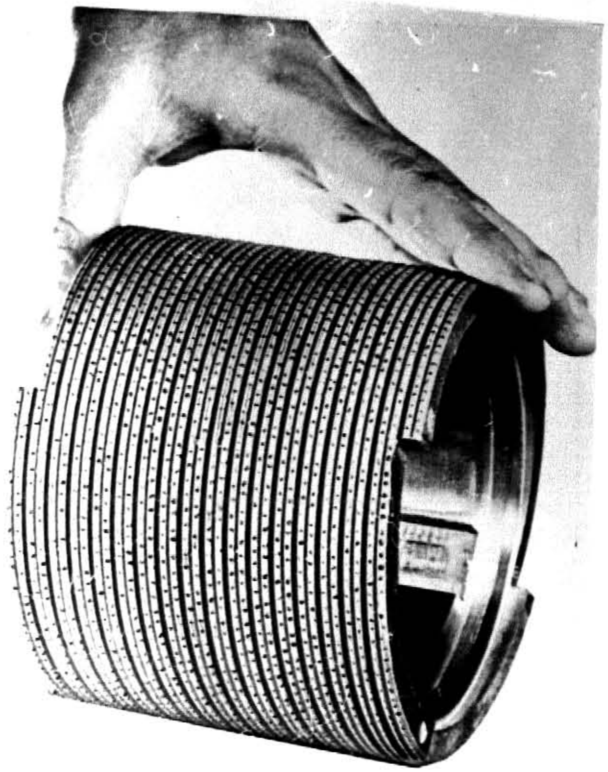

Typical Diamond Mill Cutter

Figure 1

Typical Petroleum Diamond Bit

Figure 2

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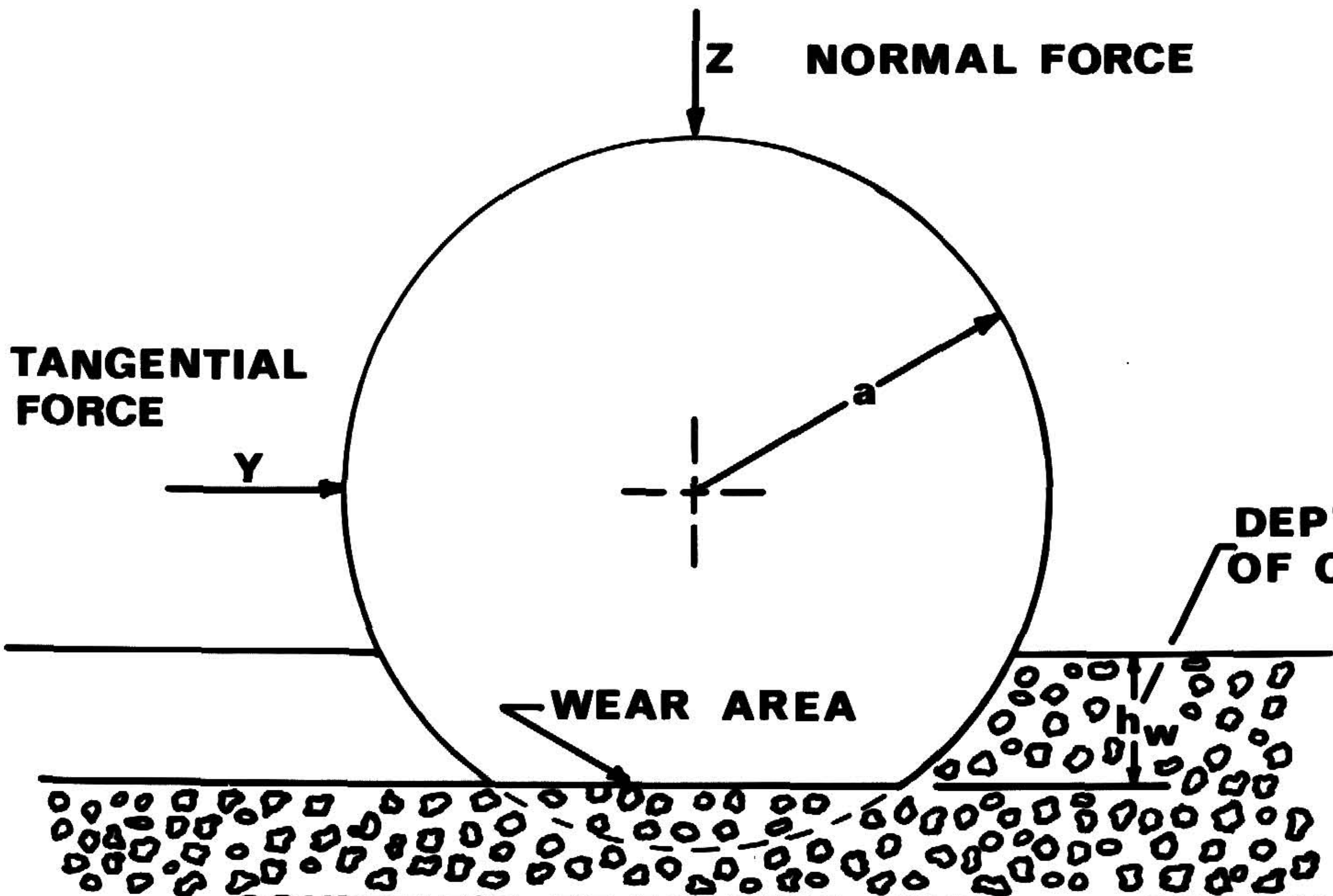


SCHEMATIC OF CUTTING WITH A WORN DIAMOND

Figure 3

The mechanism which causes the cutting surface of diamonds to wear is not entirely understood. However, those studying wear believe that the principle cause of wear is mechanical in nature. With that assumption, Appl, et. al. [1], has developed a theory for a single diamond. The purpose of this work was to obtain basic experimental data to check the validity of the theory and to obtain information relating to the rate of diamond wear. The experiment consisted of cutting on a cylindrical rock (Georgia granite) mounted in a lathe with a single spherical diamond and measuring the cutting forces.

Periodically the cutting tool was removed and photographed through a microscope to determine the nature and extent of diamond wear.

CHAPTER II

DESCRIPTION OF EXPERIMENT

The test set-up consisted of rotating a cylindrical piece of rock in a lathe. A single-point diamond tool was used to cut the rock with the forces acting on the diamond being measured with a specially built dynamometer (Fig. 4). The forces were then recorded on two Sanborn recorders. A constant flow of water was provided to keep the diamond cool and to remove the cuttings.

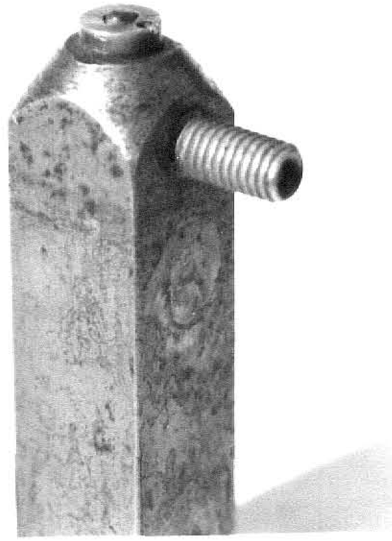
The rock used was Georgia granite. Mandrels were centered and cemented to each end for mounting in the lathe. The rock was cut to a cylinder before any tests were made.

The diamond used was initially spherical, .092 inch in diameter (8 per carat). It was mounted in a metal matrix (Fig. 5) with .040 inch protruding. This matrix was then mounted in the dynamometer.

The dynamometer used was especially designed and built for Reese [6] by Lebow and was used for this experiment with no modifications.

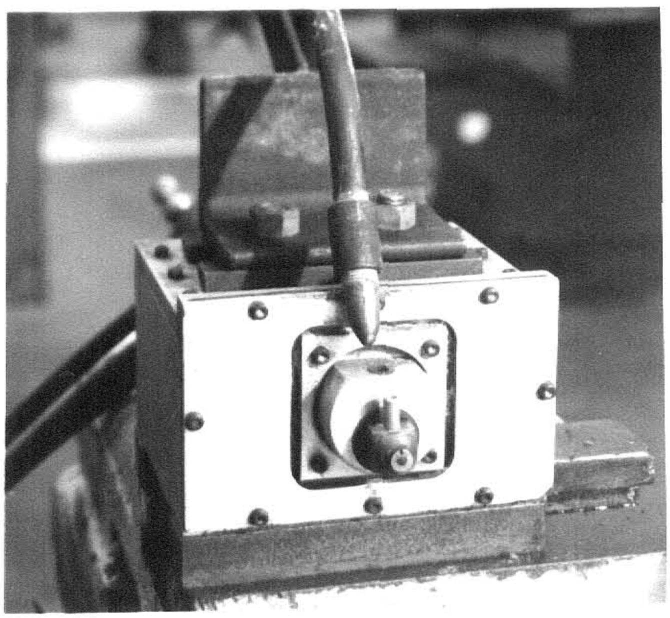
It had a range of 100 pounds in the normal direction and a 50-pound range in the axial and tangential directions. Calibrated resistors could be switched into the strain gage bridge of each direction. These resistors corresponded to a known force. By doing this, the recorders could easily be calibrated. Two channels of one recorder were used to record the normal and tangential forces. The axial force was recorded on a second Sanborn recorder. The test set-up is shown in Fig. 6.

A continuous cut was taken with the forces recorded during the entire cut. In order to find an average force for the entire cut,



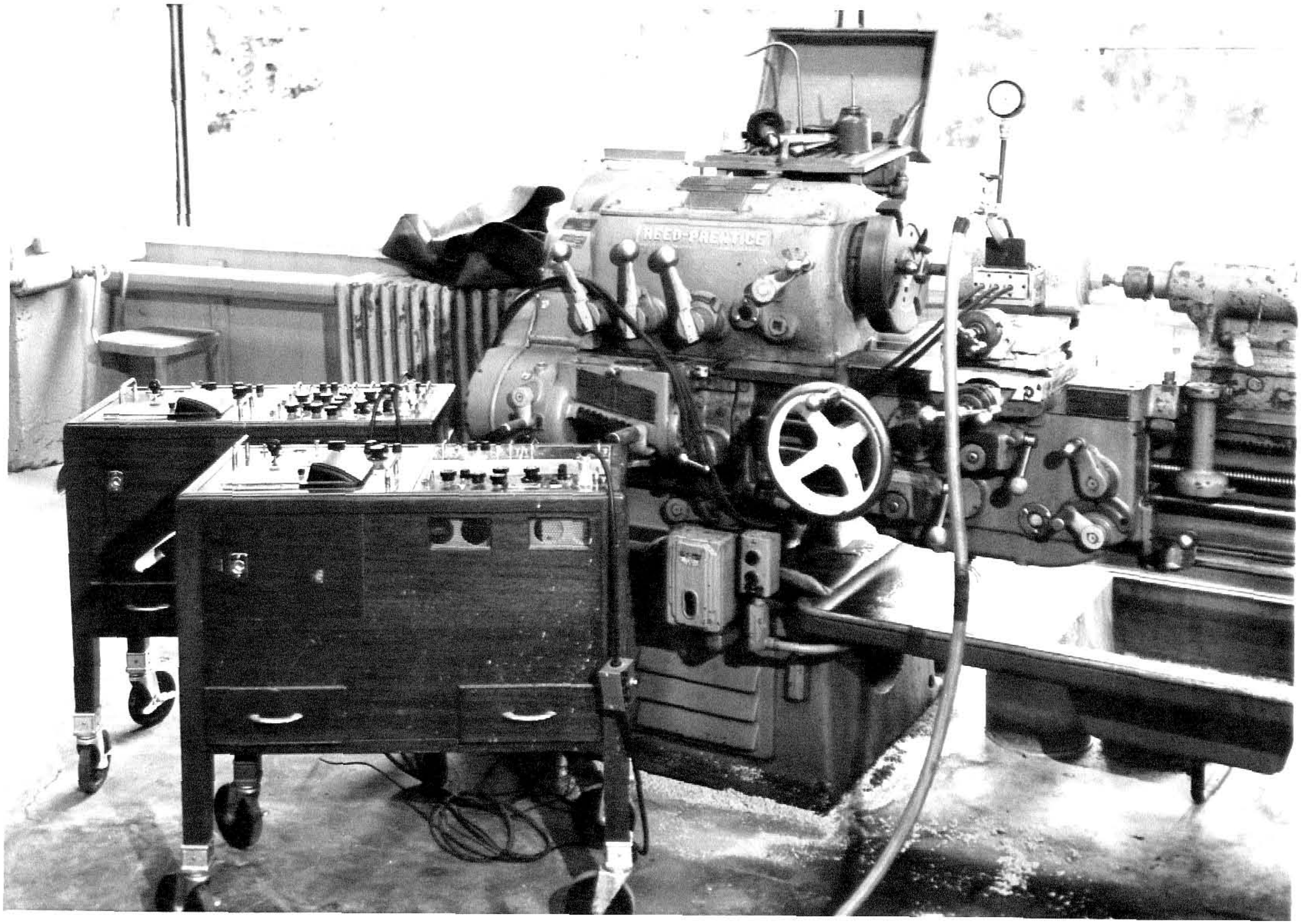
Test Diamond in Holder

Figure 5



Test Dynamometer

Figure 4



Test Set-Up

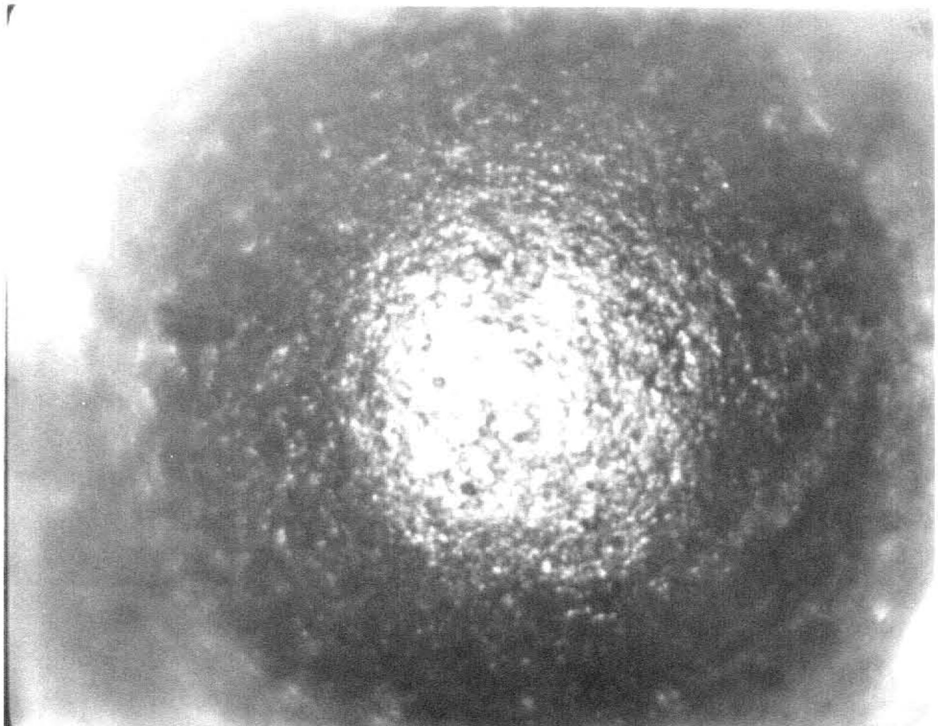
Figure 6

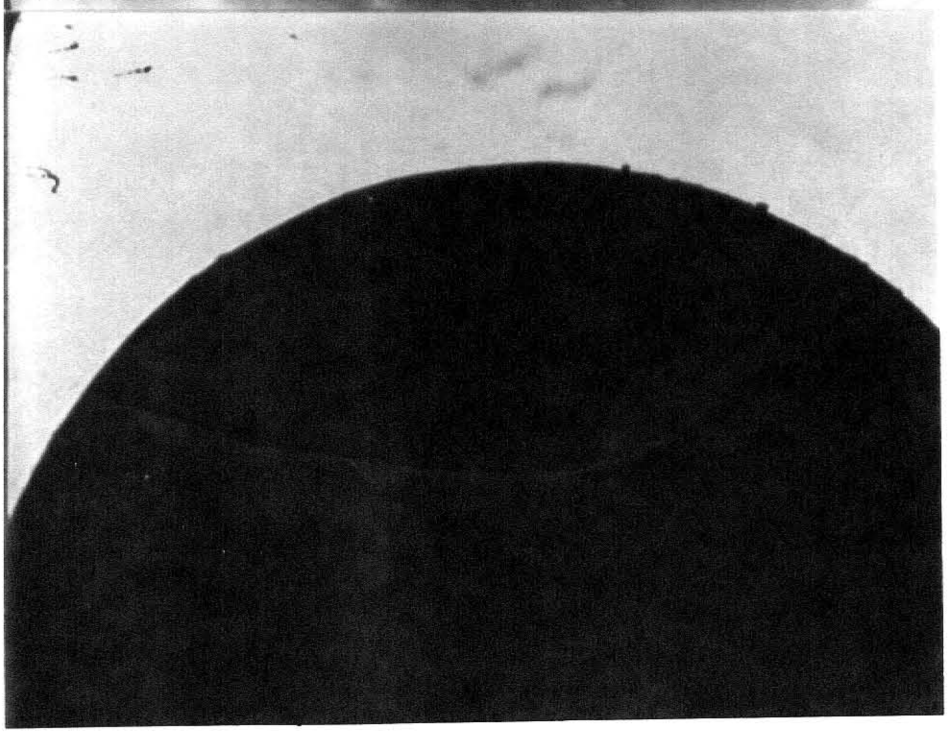
readings were taken in three places from the recordings. One reading was taken at each end and one in the center. The end readings were taken about one inch from the end of the stone so that the measured loads were unaffected by end conditions. These readings were then averaged to give a single reading for each run. After each eight runs, the diamond was removed from the dynamometer and photographed through a microscope. Typical photos are shown in Fig.'s 7, 8 and 9. Finding the area of the diamond flat spot was accomplished by two methods, yielding different areas but following similar trends.

From Fig. 8a, the area of the flat spot could be measured using a planimeter. It was assumed that the flat spots were flat. Otherwise, the entire area would not be in focus at one time. From this reading, the radius of a circle with the same area was determined. By using identities, (appendix 1) the volume of diamond worn away could be determined.

From Fig. 8b, the diameter of the flat spot could be measured. Again, by using identities, the volume of the diamond worn away could be computed.

Computer programs were written for each method and the different measurements were inserted to yield the desired information.



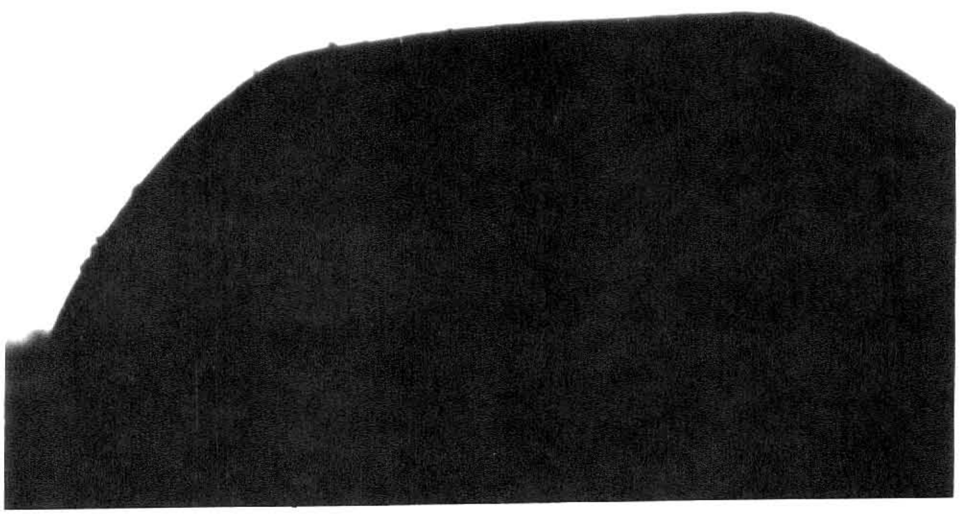


New Test Diamond (X58.6)

Figure 7a

Profile of New Test Diamond (X58.6)

Figure 7b

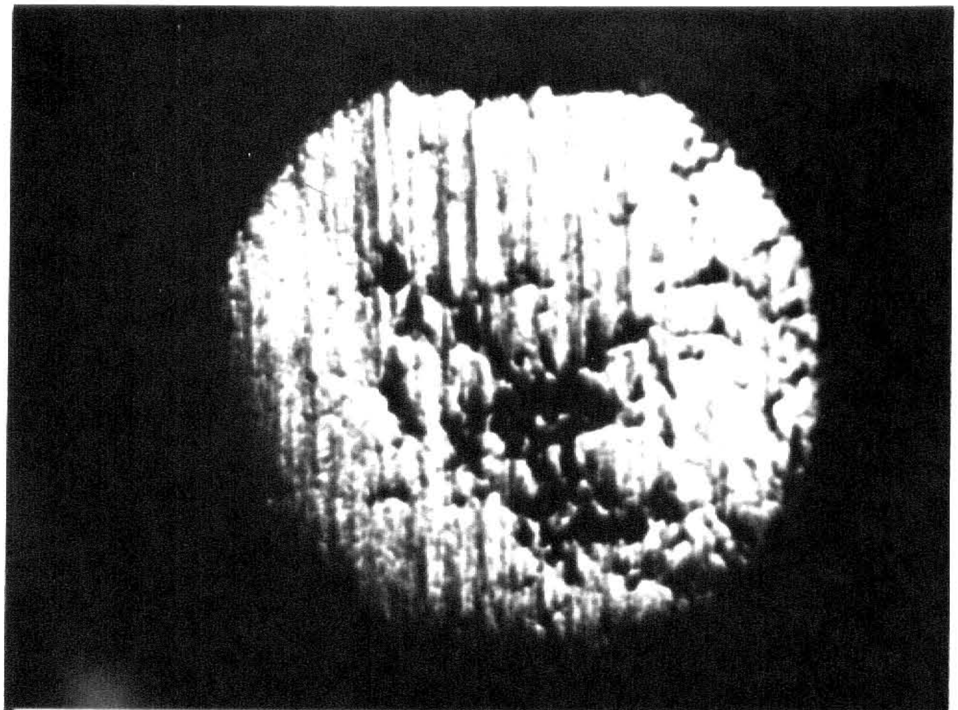


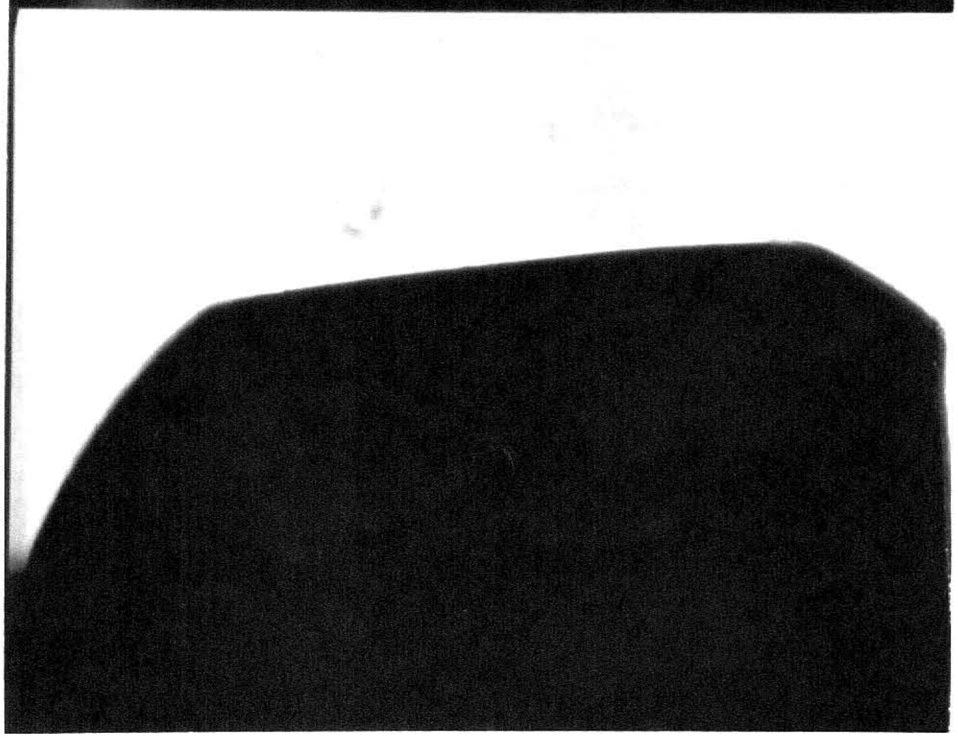
Test Diamond after 40 Runs

Figure 8a

Profile of Test Diamond after 40 Runs

Figure 8b





Test Diamond after 96 Runs

Figure 9a

Profile of Test Diamond after 96 Runs

Figure 9b

CHAPTER III

EXPERIMENTAL PROCEDURE

At the beginning of this experiment, the only cutting speed reference was by Reese. He had used a surface speed of 60 ft. per minute. This was determined to be too slow, as virtually no diamond wear was visible at the end of his test. For the second diamond, a surface speed of 435 ft. per minute was used. This was too fast, as the diamond was greatly worn after three cuts. For the third diamond, a speed of 185 ft. per minute was chosen. This again proved to give very little wear, so for diamond No. 4 a speed of 220 ft. per minute was chosen. This speed was apparently very near the natural frequency of the system as the rock vibrated very badly. The test was discontinued so that the dynamometer would not be damaged. For the final test diamond (No. 5), a beginning surface speed of 173 ft. per minute was used. Due to the fact that the lathe only had fixed speeds of rotation, the surface speed decreased somewhat as the rock became smaller. (See Table 1).

For diamonds No. 3, 4, and 5, a feed of .0025 inch per revolution and for No. 2 a feed of .005 inch was used. A cut depth of .005 inch was used for all diamonds. The cuts were overlapping so that a smooth surface was left after the diamond had passed. Once a new diamond was put into use, all conditions were left the same. The rock diameter was measured after every run.

Diamond Number	RPM	Surface Speed	Feed	Cut
2	212	435	0.005	0.005
3	91	185	0.0025	0.005
4	110	220	0.0025	0.005
5	91	173	0.0025	0.005

CUTTING CONDITIONS

Table No. 1

EXPERIMENTAL RESULTS

After cutting with diamonds No. 3 and 4, it was concluded that the diamond may fracture under severe loading. Severe loading occurred when too deep a cut was accidentally taken. Some fracturing may be desired under actual cutting conditions to provide a sharp cutting edge, but for this study fractures were not desired. A photograph of the fractured diamond is shown in Fig. 10.

When the diamond fractured, a decrease in cutting forces occurred. As the sharp edge wore away, the forces increased and eventually became higher than the level prior to fracture. When diamond No. 3 fractured, enough of the diamond broke away that further tests would have been meaningless. The diamond was not worn enough prior to this to yield any useable information.

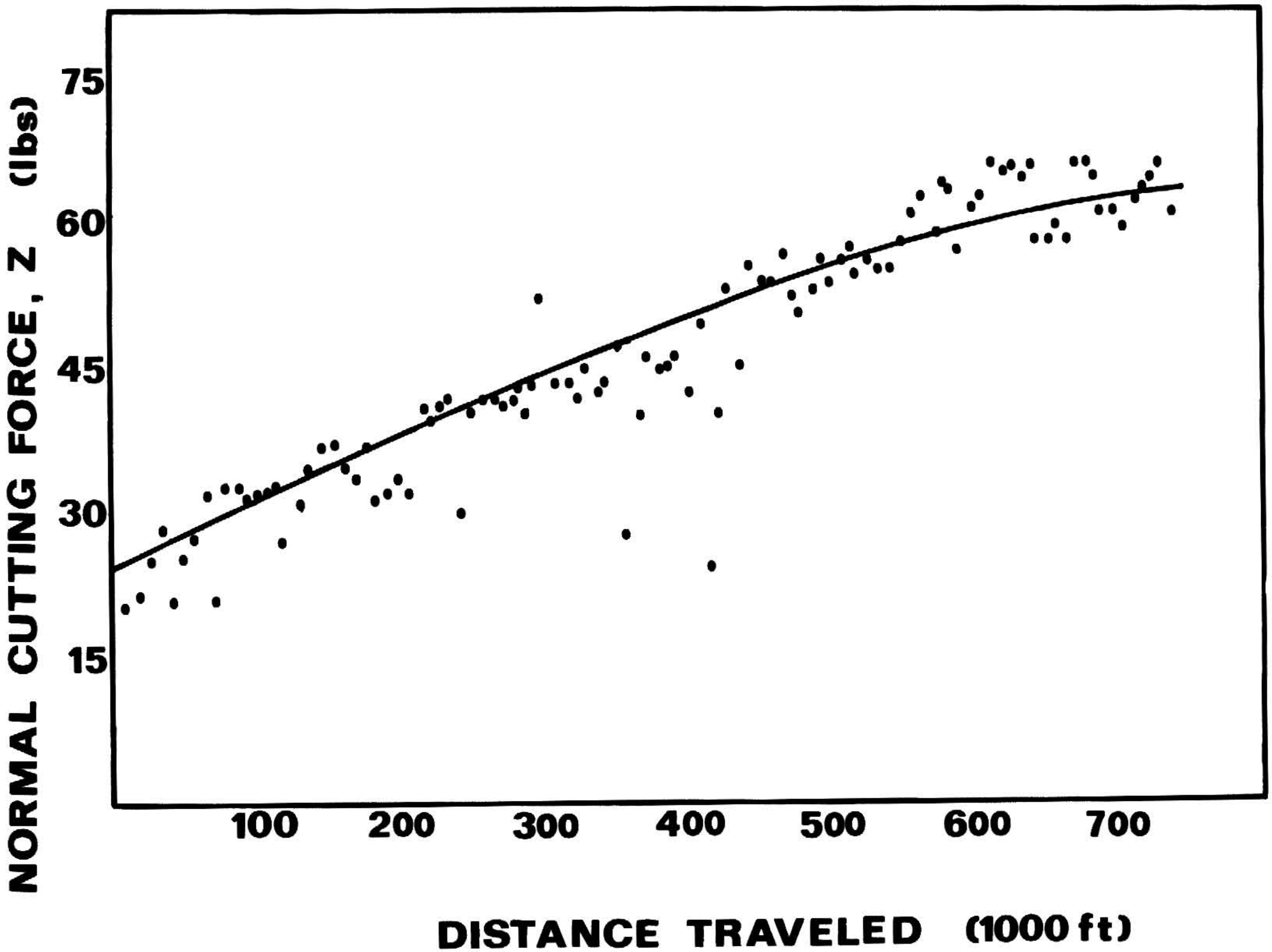
Diamond No. 4 broke on the first run in such a way that the area of the flat spot was still measureable. The tests on this diamond were continued until the vibrations became too large. It was not known whether the vibrations were due to the diamond being worn or if the speed coincided with the natural frequency of the system. The reason was assumed to be the latter because such large vibrations were not noticed with other worn diamonds.

The wear tests on diamond No. 5 proceeded very well yielding good data. The diamond wore at a slow rate, requiring a very large amount of cutting time to yield the desired results. For the final wear measurements, diamond No. 5 had traveled over 140 miles. For these reasons, all the data presented is taken from diamond No. 5.

Fractured Diamond

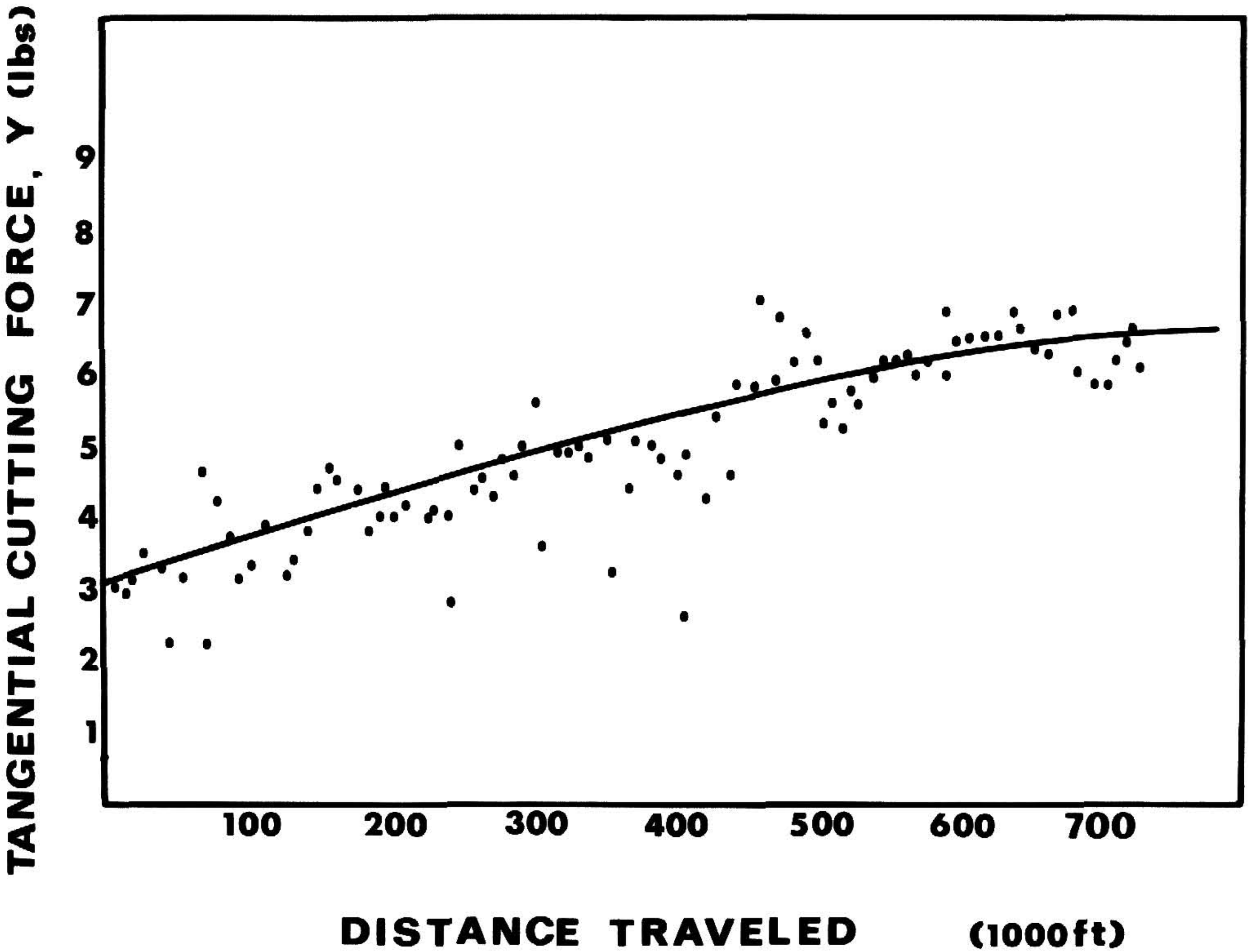
Figure 10

Fig.'s 11, 12, and 13 show how the forces changed in relationship to the distance traveled. The forces were lowest when the diamond was new, but as the diamond wore, the forces became larger. This is shown in Fig.'s 14 and 15.



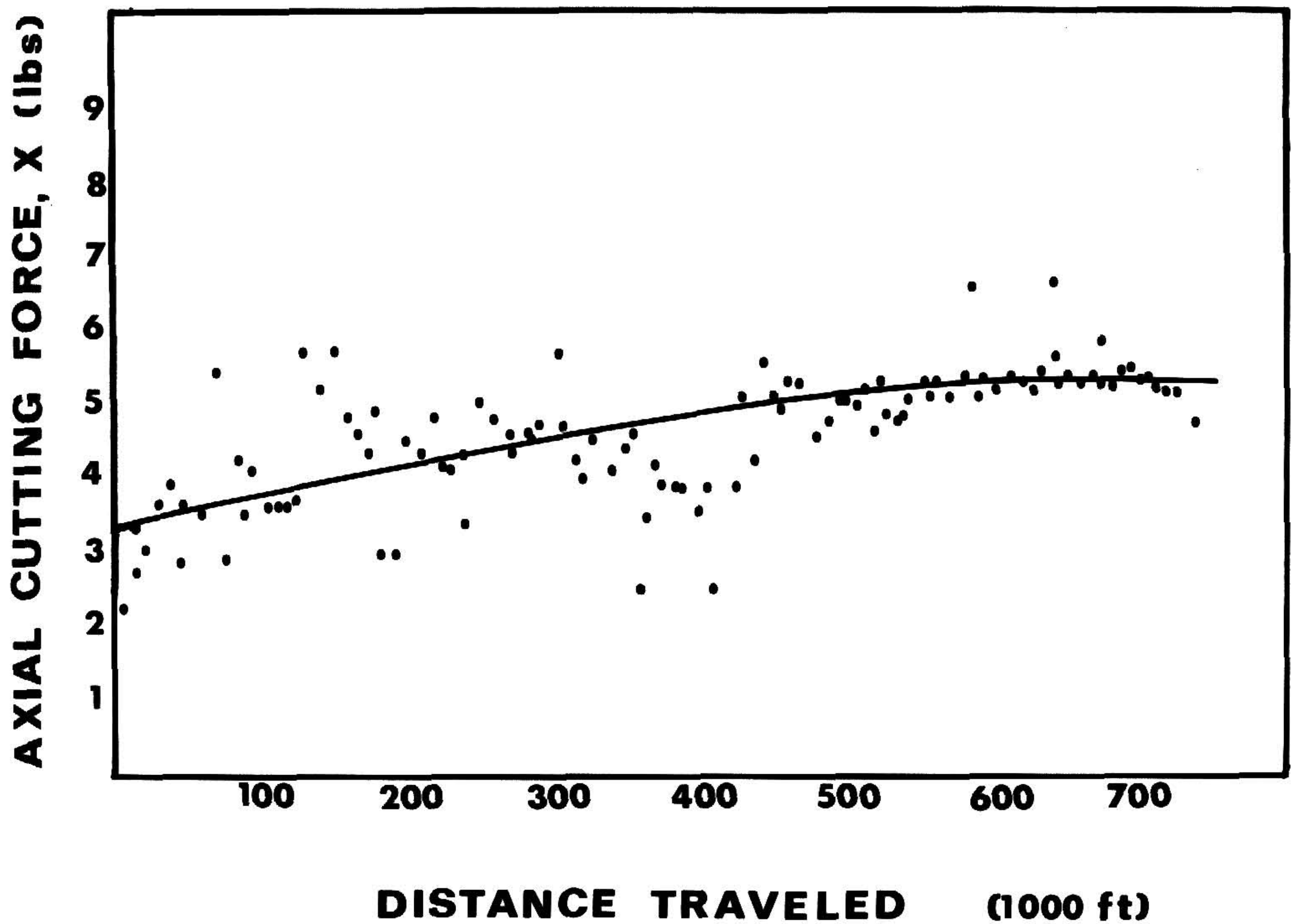
Normal Cutting Force vs. Distance Traveled

Figure 11



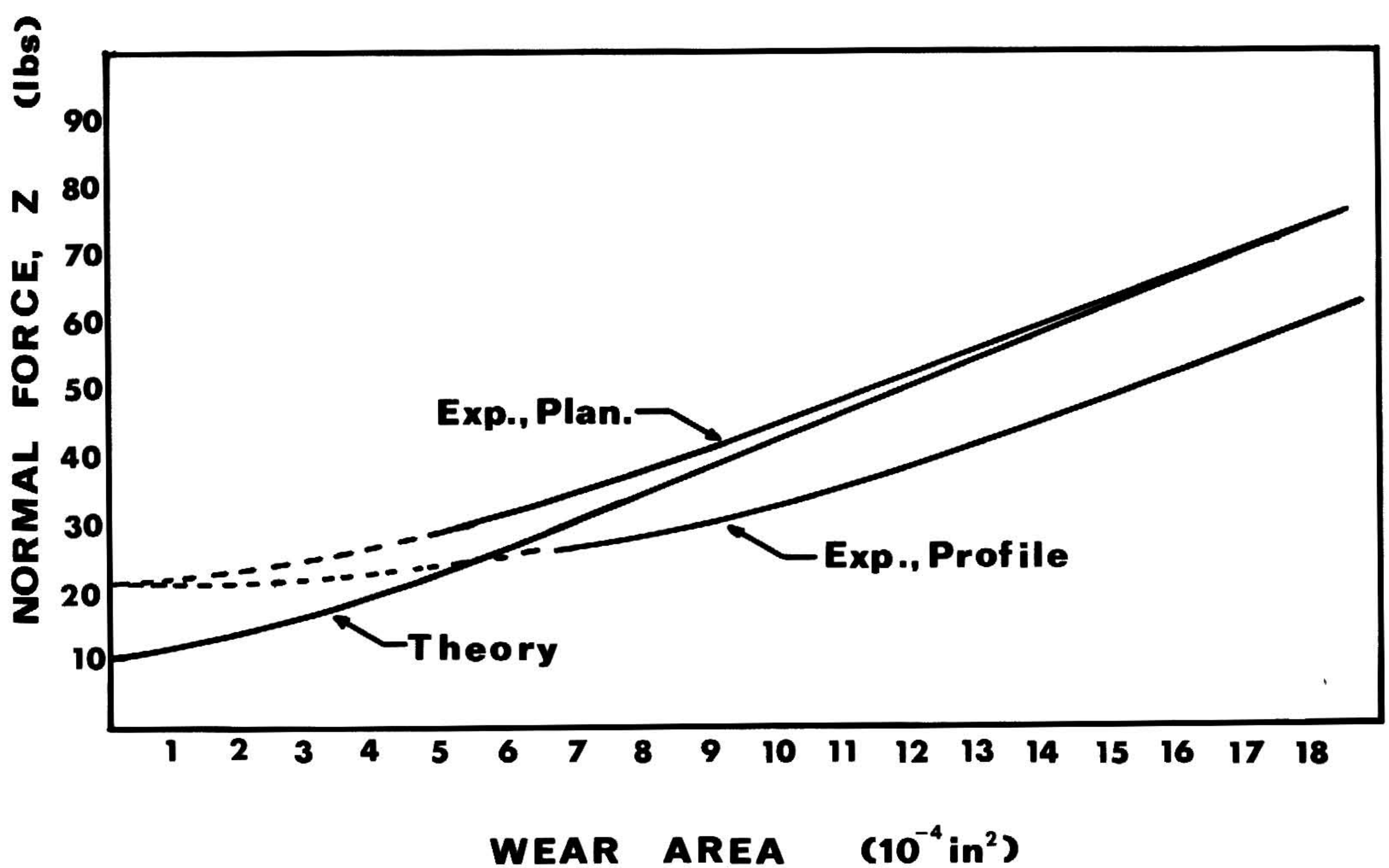
Tangential Cutting Force vs. Distance Traveled

Figure 12



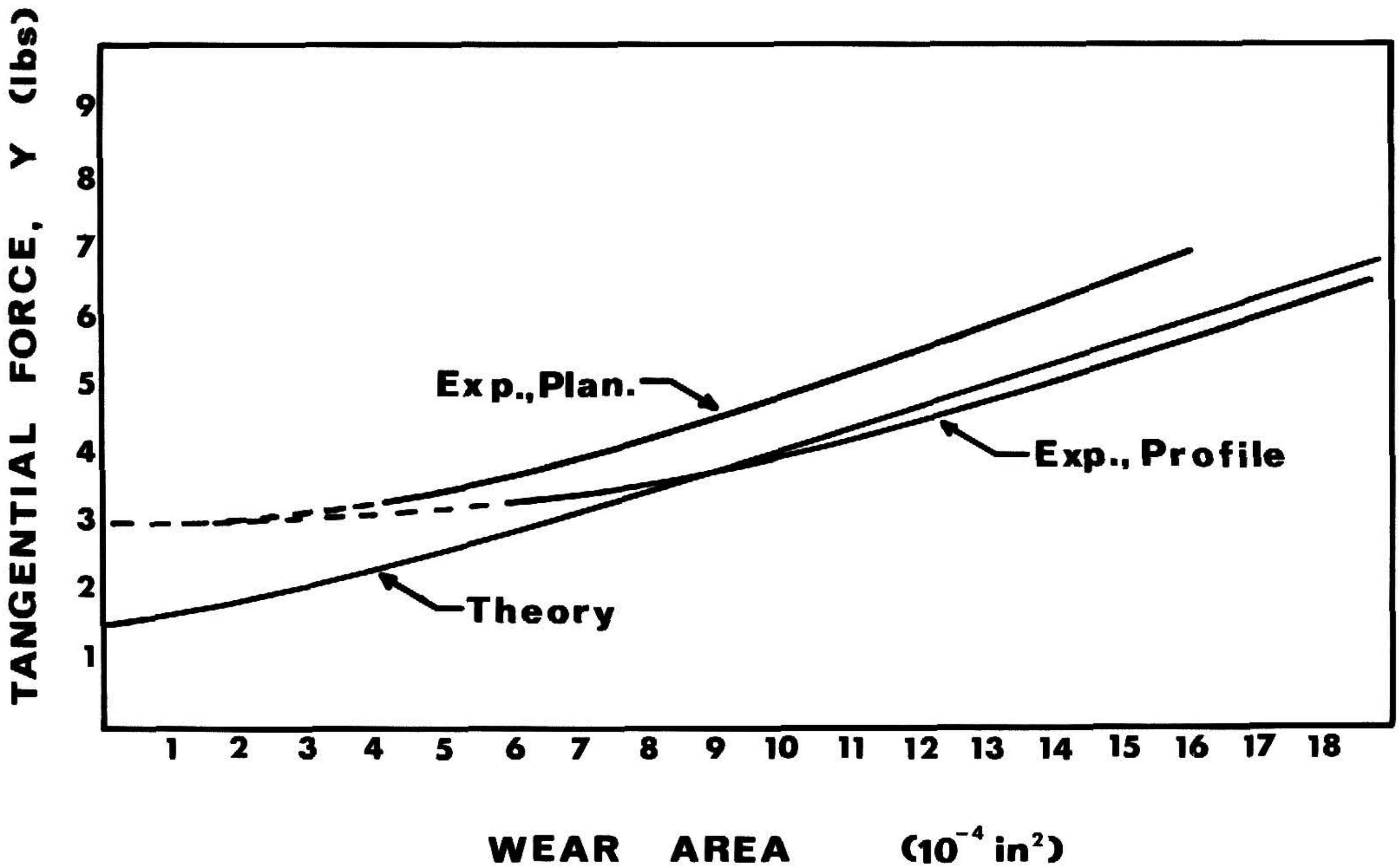
Axial Cutting Force vs. Distance Traveled

Figure 13



Normal Force vs. Wear Area

Figure 14



Tangential Force vs. Wear Area

Figure 15

By using the theory developed by Appl, (appendix 2), the data in Table 2 was obtained. This theoretical data was then plotted on the same co-ordinates as the experimental data. These graphs are shown in Fig.'s 16, 17, 18, 19, and 20.

As can be seen from Fig.'s 16 and 17, the theoretical forces were lower than the experimental forces when the diamond was new, but as the diamond wore, the curves approached the same levels. It is also seen in Fig. 18, that the experimental diamond wore faster than the theoretical diamond at first, but as the experimental wear area leveled off, the theoretical wear area surpassed it. The reasons for this are not entirely understood.

CHRISTENSEN DIAMOND PRODUCTS COMPANY
SINGLE DIAMOND CUTTING ANALYSIS

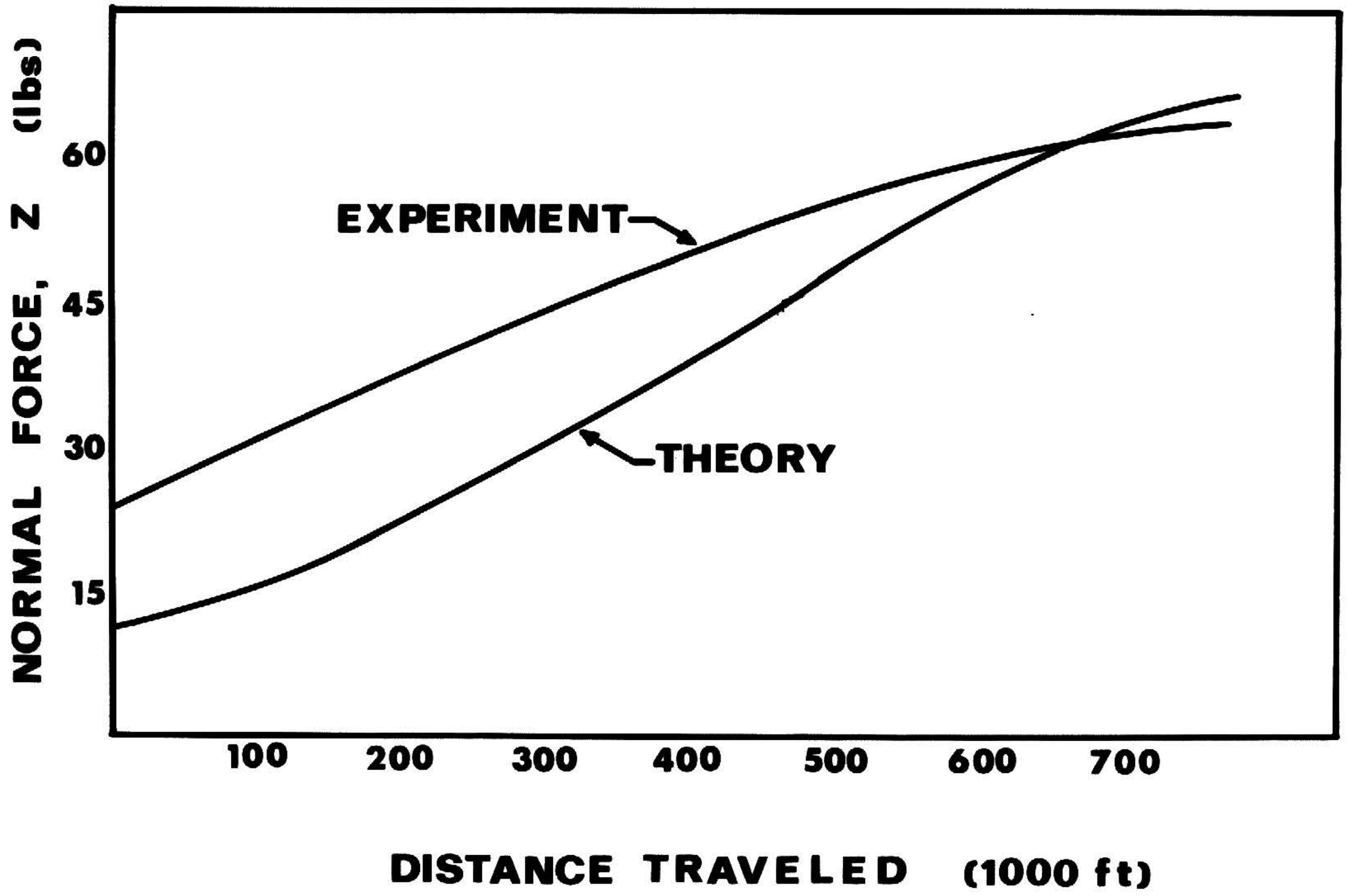
JULY 1 1972 F.C. APPL

GEORGIA GRANITE

MAXIMUM NORMAL STRESS (LB/SQ IN)... 234432.
DIAMONDS PER CARAT 8.000
RADIUS OF STONES (IN) 0.04600
ANGLE OF INTERNAL FRICTION (DEG) 50.00
COMPRESSIVE STRENGTH (LB/SQ IN) 18000.0
SHEAR STRESS AT INFINITY (LB/SQ IN).. 200000.
COEFFICIENT OF FRICTION 0.0800
CHIP SWEEP RATIO 1.100
GEORGIA GRANITE
EFFECTIVE ANGLE (DEG) 36.146
EFFECTIVE STRENGTH (LB/SQ IN) 17999.970
CONFINING PRESSURE (LB/SQ IN)...... 0.
CENTER SLICING ANGLE (DEG) 10.00
WEAR FACTOR 0.2300E-12

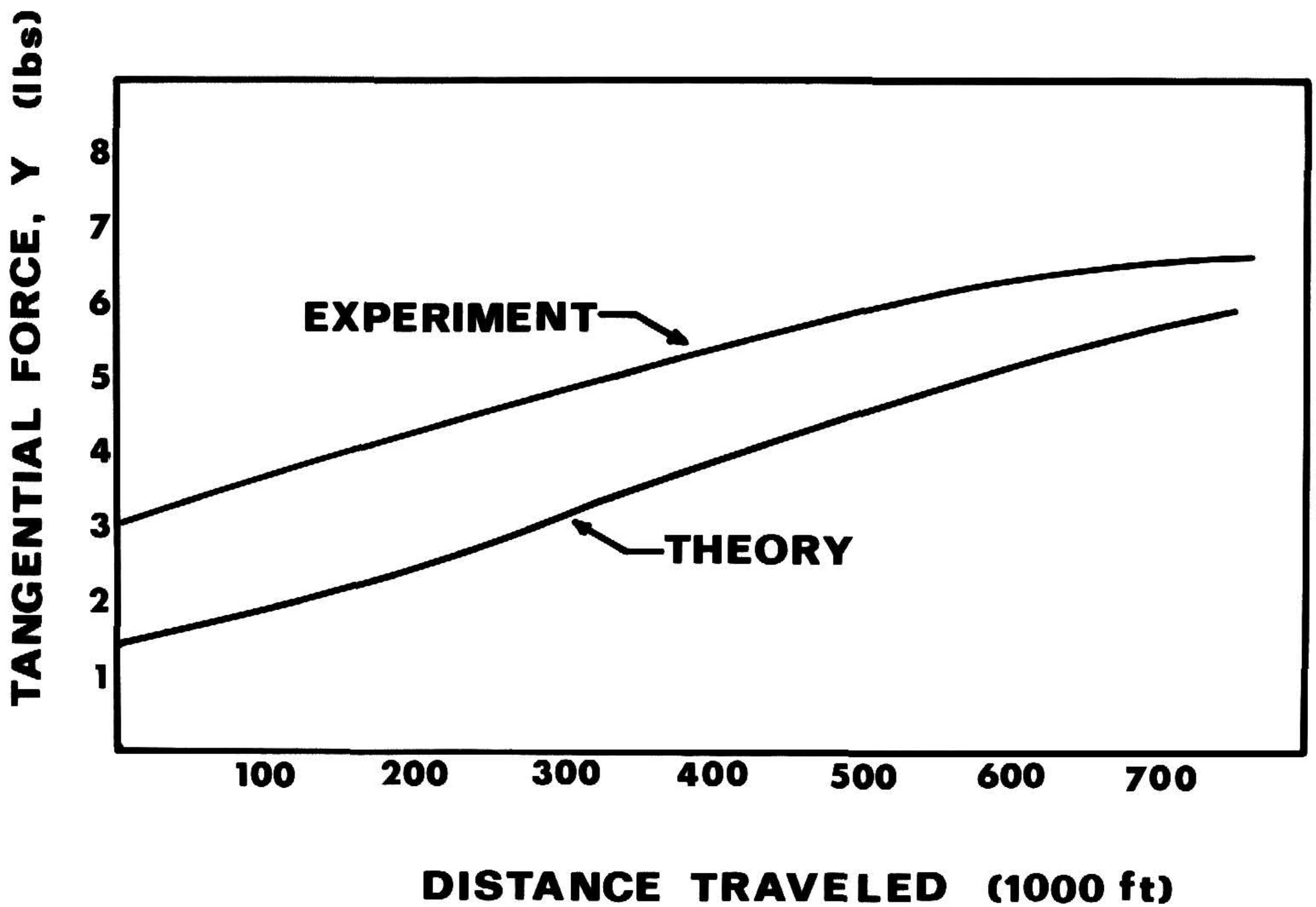
WEAR ANG	NOR LOAD	TAN LOAD	RES LOAD	CUT	LAMDA	VOLUME	WEAR AREA	WEAR DEPTH	ENERGY	DISTANCE
0.	12.7497	1.72365	12.8657	0.0009261	11.517	0.00001250	0.00000	0.0000	137889.	0.
2.	12.6663	1.73639	12.7848	0.0009014	11.537	0.00001250	0.00001	0.0000	138910.	3066.
4.	12.6363	1.77576	12.7605	0.0008399	11.677	0.00001250	0.00003	0.0001	142078.	12258.
6.	12.9663	1.84707	13.0969	0.0007601	12.041	0.00001250	0.00007	0.0003	147783.	27567.
8.	13.8947	1.95783	14.0320	0.0006765	12.693	0.00001250	0.00013	0.0004	156631.	48973.
10.	15.5672	2.11481	15.7102	0.0005985	13.640	0.00001250	0.00020	0.0007	169183.	76451.
12.	18.0352	2.32113	18.1840	0.0005299	14.844	0.00001249	0.00029	0.0010	185819.	109966.
14.	21.3027	2.58074	21.4585	0.0004724	16.255	0.00001250	0.00039	0.0014	206512.	149478.
16.	25.3238	2.89141	25.4883	0.0004243	17.817	0.00001250	0.00051	0.0018	231333.	194940.
18.	30.0493	3.25173	30.2253	0.0003842	19.489	0.00001250	0.00063	0.0023	260144.	246294.
20.	35.4296	3.65960	35.6181	0.0003506	21.240	0.00001250	0.00078	0.0028	292766.	303480.
22.	41.4125	4.11278	41.6162	0.0003224	23.048	0.00001250	0.00093	0.0033	329018.	366427.
24.	47.9494	4.60827	48.1703	0.0002984	24.898	0.00001250	0.00110	0.0040	368655.	435057.
26.	54.3944	5.14369	55.2344	0.0002781	26.779	0.00001251	0.00128	0.0047	411200.	509290.
28.	62.4971	5.71463	62.7579	0.0002603	28.683	0.00001251	0.00147	0.0054	456946.	589032.
30.	70.4136	6.31844	70.6965	0.0002449	30.605	0.00001250	0.00166	0.0062	505292.	674189.
32.	78.6973	6.95276	79.0037	0.0002314	32.540	0.00001250	0.00187	0.0070	556034.	764655.

THEORETICAL RESULTS



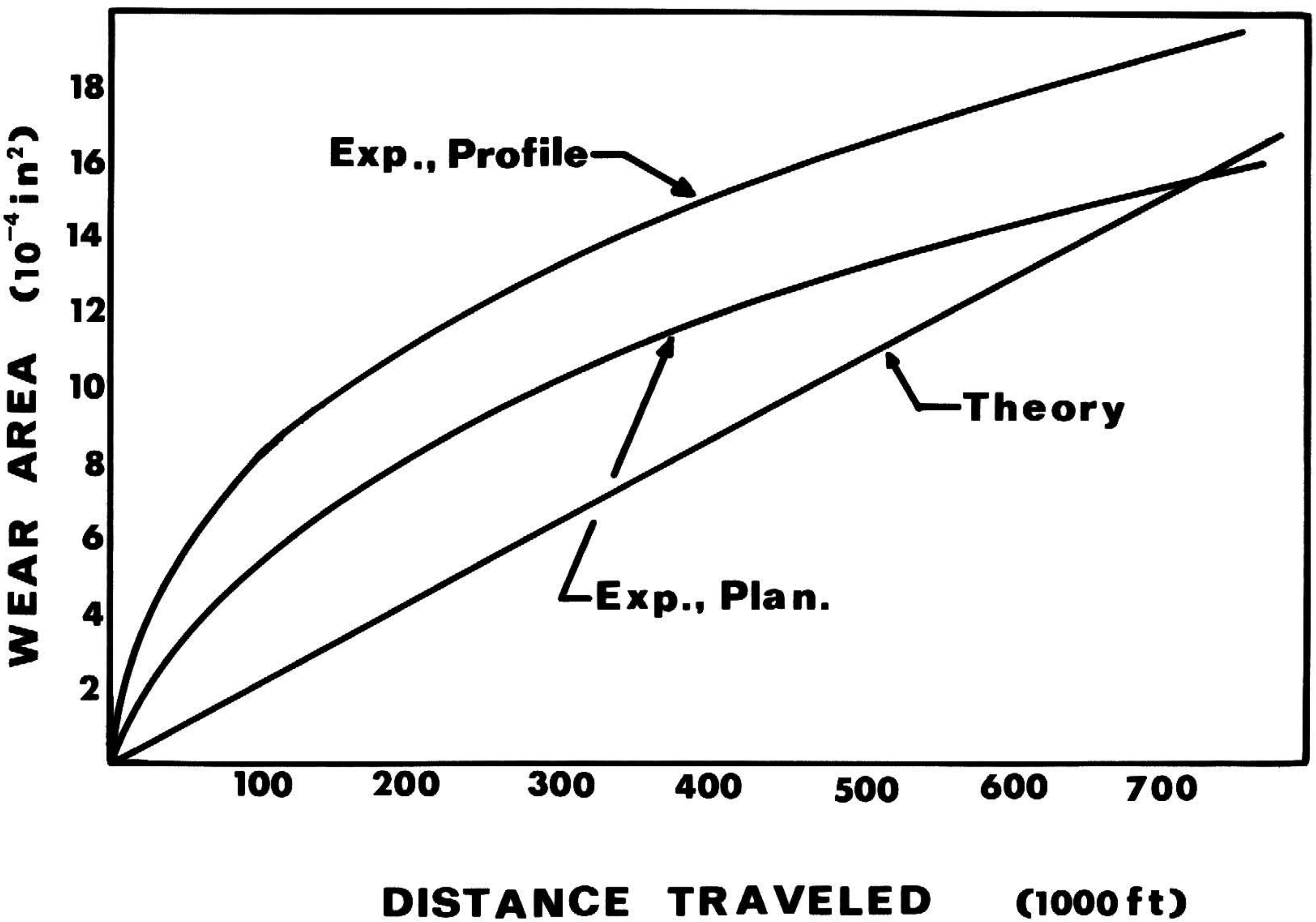
Normal Force vs. Distance Traveled

Figure 16



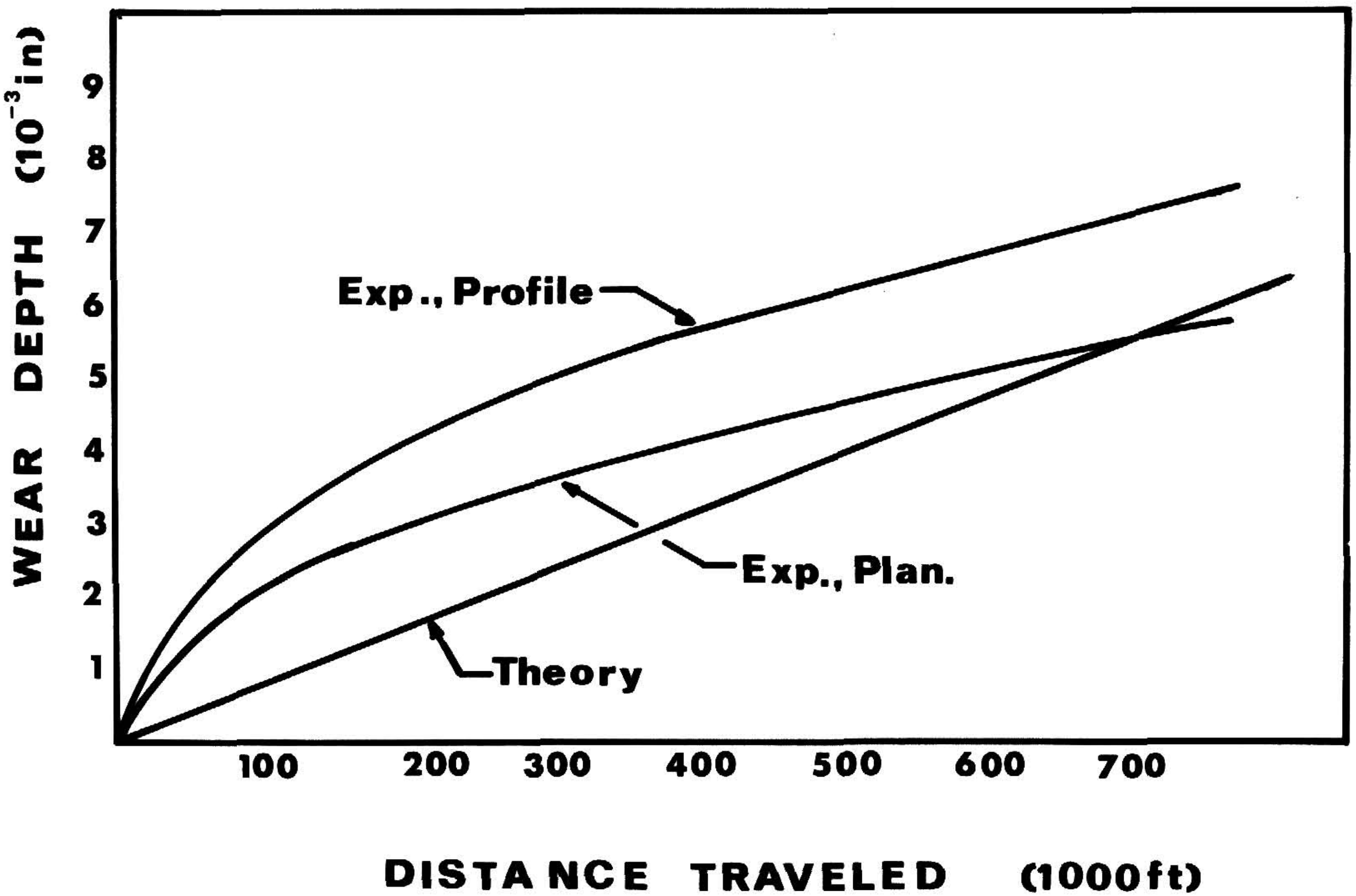
Tangential Force vs. Distance Traveled

Figure 17



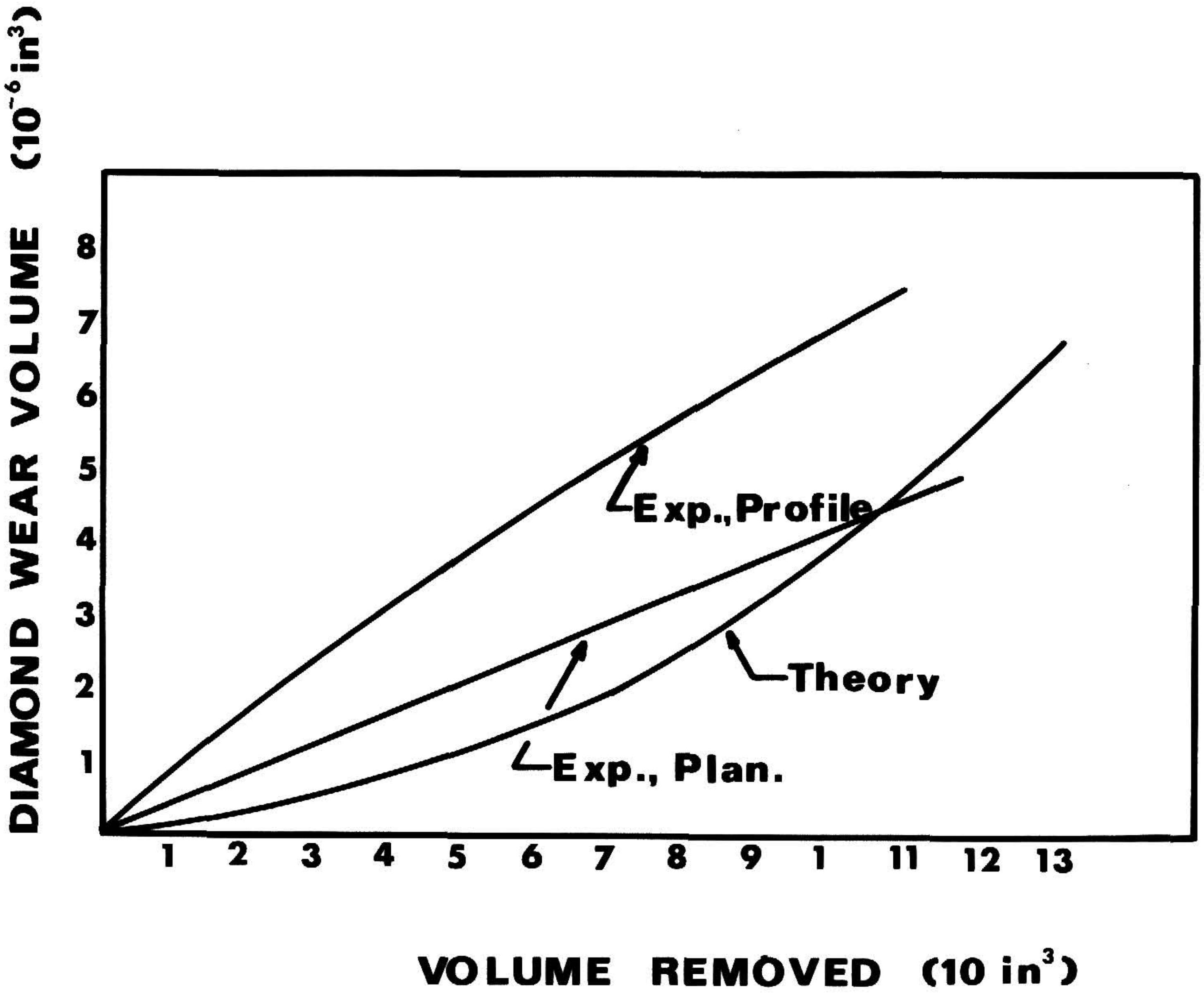
Wear Area vs. Distance Traveled

Figure 18



Wear Depth vs. Distance Traveled

Figure 19



Diamond Wear Volume vs. Volume Removed

Figure 20

CHAPTER V

CONCLUSION

The forces were analyzed in relation to cutting distance and wear area. It was found that there was a definite relationship between the rate of wear and the cutting speed, but because of the time element, this was not considered.

It is felt that this study is valid and a good beginning point for further studies. It is important to learn more about the speed effect. This will require that data for several different speeds be obtained.

CHAPTER VI

RECOMMENDATIONS

To enhance the value of this work, several additional tests need to be made. Other types of rock should be tested, as granite is a small part of the rock cut in practice.

Another variable not considered was diamond size. All the tests were based on a .092 inch diamond. It is expected that similar results would be obtained for diamonds of other size, but this should be verified experimentally.

A lathe with variable speed is recommended for further tests. This would allow the cutting speed to be held constant.

It would also be helpful if a method to measure diamond wear area could be devised that did not require that the diamond be removed from the dynamometer. This would reduce the possibility of taking too deep a cut which could cause premature diamond fracture.

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APPENDIX 1

COMPUTER PROGRAM

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 ?J?B           FCA
   41 DIMENSION VOL(95), ??(95),          P1(95), P2(95), CUT(95),WR(95)
   42 DIMENSION TAN(95), PL(95), ENNF(95),PSIW1(95),DIS(95),WRAR(95),
     1WRDPE(95)
   44 DIMENSION PN1(95), PN2(95), Z1(96), Z2(96),IEARTH(10),NOTE(10)
      INTEGER TELL(24)
      LOGICAL   SWTCH1,SWTCH2,SWTCH3,SWTCH4
      LOGICAL FIRSTL
      FIRSTL=.FALSE.
    1 FORMAT(6F10.0)
    2 FORMAT (1H )
    4 FORMAT(1H0/1H,'WEAR ANG',1X,'NOR LOAD',4X,'TAN LOAD',3X,
     1 'RES LOAD', 8X,'CUT',6X,'LAMDA',7X,'VOLUME',6X,'WEAR AREA',2X,
     2 'WEAR DEPTH',3X,'ENERGY',8X,'DISTANCE')
    5 FORMAT(F10.4)
   26 FORMAT(6X41 H     CONFINING PRESSURE (LB/SQ IN)......    , F9.0)
   24 FORMAT(6X41 H     MAXIMUM NORMAL STRESS (LB/SQ IN)...    , F9.0)
   13 FORMAT( 6X 41 H     DIAMONDS PER CARAT .................. , F10.3)
   32 FORMAT(6X43 H     RADIUS OF STONES (IN) ............... , F12.5)
   31 FORMAT(6X43 H     ANGLE OF INTERNAL FRICTION (DEG) .... , F9.2)
   14 FORMAT(6X43 H     COMPRESSIVE STRENGTH (LB/SQ IN) ..... , F 8.1)
   29 FORMAT( 6X 43H     SHEAR STRESS AT INFINITY (LB/SQ IN)..    F7.0 )
   12 FORMAT( 6X43 H     COEFFICIENT OF FRICTION ............. , F11.4)
    6 FORMAT(6X43 H     CHIP SWEEP RATIO .................... , F10.3)
    8 FORMAT(11X 10A3)
   17 FORMAT(6X43H     EFFECTIVE ANGLE (DEG) ...............  F10.3  )
   19 FORMAT(7X41H    EFFECTIVE STRENGTH (LB/SQ IN) .......          F11.3)
   21 FORMAT(6X 43H     CENTER SLIDING ANGLE (DEG) .......... , F9.2 )
   36 FORMAT(1H,F5.0,2X,F10.4,2X,F10.5,1X,F10.4,2X,F11.7,4X,F8.3,4X,
     1F10.8,4X,F8.5,4X,F7.4,3X,F8.C,2X,F11.0)
   38 FORMAT(6X43H     WEAR FACTOR ........................... ,E12.4)
      DATA LAST/3HEND/
C--------READ SENSE SWITCHES,DATE AND NUMBER COPIES IN COLS 35-39
   45 READ(5,1255)SWTCH1,SWTCH2,SWTCH3,SWTCH4,(NOTE(IX),IX=1,10),ICOPYS
      IF(NOTE(2).EQ.LAST) GO TO 1467
 1255 FORMAT(4L1,10A3,I5)
      IF(ICOPYS.LT.1) ICOPYS = 1
      FIRSTL=.FALSE.
C
C     READ FORMATION PARAMETERS
C
   50 READ(5,1) SIGM, TAUI
   52 READ(5,1) ALPD
      READ(5,5)WKS
C     READ BIT PARAMETERS  AND RUN DESCRIPTION
      READ(5,1256) TELL
 1256 FORMAT(24A3)
   54 READ(5,1) AC
   59 READ(5,1) DPC
      READ(5,1)PSIWW,DELPSI,PSIMAX
C     READ DRILLING PARAMETERS
   63 READ(5,9) IEARTH
    9 FORMAT(10A3)
   68 READ(5,1) VCVD
      SIGC=0.0
C     READ PERCENT ERROR SQUARED FOR (2 LAMDA-2SIN 2LAMDA)
      ERRQ=.000001
C
      ERRR=.CC0001
      ERRZ=.C0001
```

```
C
C     READ COEFFICIENT OF FRICTION
   71 READ(5,1) F
C     READ CENTER SLIDING ANGLE
  171 READ(5,1) CC
      READ(5,1)VOL(1)
   72 PI=3.1415927
   73 PIC=PI/180.0
  200 CONTINUE
  202 IF (CC) 204,204,220
  204 TJ1=1.0
  206 TJ2=1.0
  208 TJ3=0.0
  210 TJ4=0.0
  212 TJ5=0.0
  214 TJ6=0.0
  216 GO TO 406
  220 IF (CC-90.0) 240,222,222
  222 TJ1=PI/4.0
  224 TJ2=((PI*PI)/16.0)+0.25
  226 TJ3=1.0
  228 TJ4=(PI/2.0)-1.0
  230 TJ5=TJ1
  232 TJ6=TJ2-0.5
  234 GO TO 406
  240 C=CC*PIC
  242 TM=(2.0*C)/PI
  244 SINO=SIN((PI/2.0)-C)
  246 COSO=COS((PI/2.0)-C)
  248 TMP1=TM+1.0
  250 TMM1=TM-1.0
  252 PIQ2=PI/2.0
  254 SINM1=SIN(PIQ2*TMM1)
  256 SINP1=SIN(PIQ2*TMP1)
  258 COSM1=COS(PIQ2*TMM1)
  260 COSP1=COS(PIQ2*TMP1)
  262 SINM=SIN(PIQ2*TM)
  264 COSM=COS(PIQ2*TM)
  270 TT1=(COSO*SINM1+SINO*(COSM1-1.0))/(2.0*TMM1)
  272 TT2=(COSO*SINP1+SINO*(COSP1-1.0))/(2.0*TMP1)
  274 TJ1=TT1-TT2
  276 TJ5=TT1+TT2
  278 TT1=COSO*(PIQ2*SINM1+(COSM1-1.0)/TMM1)
  280 TT1=((SINO*(PIQ2*COSM1-SINM1/TMM1))+TT1)/(2.0*TMM1)
  282 TT2=COSO*(PIQ2*SINP1+(COSP1-1.0)/TMP1)
  284 TT2=((SINO*(PIQ2*COSP1-SINP1/TMP1))+TT2)/(2.0*TMP1)
  286 TJ2=TT1-TT2
  288 TJ6=TT1+TT2
  290 TJ3=(COSO*SINM+SINO*(COSM-1.0))/TM
  292 TJ4=COSO*((COSM-1.0)/TM+PIQ2*SINM)
  294 TJ4=(TJ4-(SINO*(SINM/TM-PIQ2*COSM)))/TM
  406 CONTINUE
      ALPR=ALPD*PIC
  410 AD2=AC*AD
  420 SINAL=SIN (ALPR)
  422 COSAL=COS (ALPR)
      TAUO=SIGM*(1.0-SINAL)/(2.0*COSAL)
      RETO=SINAL/COSAL
      SIGX=SIGC+100000.0
      B=TAUI-TAUO
```

```
      PSI*=(0.0)
      PSI=PETU/B
  453 DELALP=0.1
      ALP=ALPW
      KKT=1
  437 SINAL=SIN(ALP)
      COSAL=COS(ALP)
      TANALP=SINAL/COSAL
      TAU=SIGM*(1.0-SINAL)/(2.0*CCSAL)
      PSX=PSI*SIGX
      PSX2=PSX*PSX
      EPX=EXP(-PSX)
      G=((TALI-TAU)/B)*(2.0*TAU/SIGX-1.0/COSAL)
      G=G-TAL*TANALP/B+2.0*SIGX*SINAL/(3.0*B*CCSAL*COSAL)
      G=G+2.C*TAU*(EPX-1.0)/(PSX*SIGX)
      G=G-2.0*((PSX+1.0)*EPX-1.0)/(PSX2*COSAL)
      IF(KKT-1)439,439,441
  439 GG=G
      ALPI=ALP
      ALP=ALF-DELALP
      KKT=2
      GOTO437
  441 IF(GG/G)447,443,443
  443 ALPI=ALP
      GG=G
      ALP=ALP-DELALP
      GOTC437
  447 ERR=(ALPI-ALP)*(ALPI-ALP)/(ALP*ALP)
C     WRITE(3,3)ALP,ALPI,G,GG,ERR
      IF(ERR-ERRR)451,451,449
  449 DELALP=DELALP/2.0
      ALP=ALP+DELALP
      GOTO437
  451 ALD=ALF/PIC
      SINAL=SIN(ALP)
      COSAL=COS(ALP)
      A1=0.5*(1.0+SINAL)/SINAL
      A2=0.5*(1.0-SINAL)/SINAL
      BET=SINAL/COSAL
      PIB=PI*BET
      EPIB=EXP(PIB)
      EPSW=EXP(BET*(PI-2.0*PSIW))
      SIG=(TAU+BET*SIGC)*2.0*COSAL/(1.0-SINAL)
      SIGX1=SIG*((A1*EPSW)-A2)+SIGC
      ER=(SIGX1-SIGX)*(SIGX1-SIGX)/(SIGX1*SIGX1)
      IF(SWITCH1) WRITE(6,1) ER
      IF(ER-ERRZ) 433,433,435
  435 SIGX=(SIGX1+SIGX)/2.0
      GOTO453
  433 SIGMA=SIG
      STRB=2.3*SIGMA
      ALD=ALF/PIC
      SI=TAU+2.0*COSAL/(1.0-SINAL)
      SMX=SIGMA*((A1*EPSB)-A2)
  434 BXB=BET*BET
  436 BXB1=BXB+1.0
  438 BIN=1.C/BET
      I=0
  340 CONTINUE
      I=I+1
```

```
      PSIW(I)=PSIWW+(I-1)*DELPSI
      PSIW=PSIW(I)*PIC
      SINPSW=SIN(PSIW)
      VOL(I)=VOL(I)
      CAP1=0.0
      APPR1=PSIW
      Q=2.0*VOL(I)/(AD2*VCVD)
      APPR2=(0.75*Q)**0.33+PSIW
  316 APX2=2.0*APPR2
      QAP2=APX2-SIN(APX2)-(2.0*PSIW-SIN(2.0*PSIW))
      ERR1=Q-QAP2
      ERR=ERR1/QAP2
      ERROR=ERR*ERR
      IF(ERROR-ERRC)337,337,326
  326 APPR3=APPR2
      APPR2=APPR2+((APPR2-APPR1)/(CAP2-CAP1))*ERR1
      CAP1=CAP2
      APPR1=APPR3
      GO TO 316
  337 TAM=APPR2
      TAMD(I)=TAM/PIC
      CUT(I)=AD*(COS(PSIW)-COS(TAM))
  342 SINLA=SIN (TAM)
      COSLA=COS(TAM)
  344 TAMX2=2.0*TAM
  346 SIN2L=SIN (TAMX2)
  347 COS2L=COS (TAMX2)
  348 BLXM2=(-2.)*BET*TAM
  350 EM2BL=EXP (BLXM2)
      EM2BP=EXP(-2.0*BET*PSIW)
  352 P2N=((2.*BET*SINLA*SINLA)+SIN2L+BIN)*(-EM2BL)
      P2N=P2N+EM2BP*(2 .0*BET*SIN(PSIW)*SIN(PSIW)+SIN(2.0*PSIW)+BIN)
      P2N=P2N*A1*EPIB
      P2N=((P2N/BXB1)+(A2*(SIN2L-TAMX2-SIN(2.0*PSIW)+2.0*PSIW)))
  356 P1S=P2N*((TJ3/2.0)-(TJ4/PI))
  357 P2N=P2N/PI
  358 PN2(I)=P2N*AD2*SIGMA
      PIN=(EM2BP*(BET*SIN(2.0*PSIW)+COS(2.0*PSIW)))-(EM2BL*((BET*
     1SIN2L)+COS2L))
  362 PIN=(PIN*A1)/BXB1
      PIN=(PIN*EPIB)+A2*(COS2L-COS(2.0*PSIW))
  366 PIN=(PIN*PI)/8.0
      PN1(I)=PIN*AD2*SIGMA+PI*STRB*AD2*SIN(PSIW)*SIN(PSIW)
  503 P1SU=P1S*U
  504 TT1=(2.0*TJ1)-((4.0*TJ2)/PI)
  506 TT2=(2.0*TJ5)-((4.0*TJ6)/PI)
  508 P2S=TT1*A1*EPIB
      P2S=P2S*((EM2BP*(2.0*BET*SIN(PSIW)+COS(PSIW))
     1-((EM2BL)*((2.0*BET*SINLA)+COSLA)))/((4.0*BXB)+1.0))
  512 P2SS=(TT2*A1*EPIB)/(4.0*BXB1)
      P2SS=P2SS*(-((EM2BL)*((BET*SIN2L)+COS2L))+EM2BP*(BET*SIN(2.0*
     1PSIW)+COS(2.0*PSIW)))
      P2SSS=(TT1*(COSLA-COS(PSIW)))+((TT2/4.0)*(COS(2.0*PSIW)-COS2L))
  520 P2S=(P2SSS*A2)-P2SS   +P2S
  522 P2SU=U*P2S
  524 P1A =(PIN+P1SU)
      P1(I)=P1A*AD2*SIGMA+PI*AD2*STRB*SIN(PSIW)*SIN(PSIW)
  526 P2A =(P2N+P2SU)
      P2(I)=P2A*AD2*SIGMA+PI*AD2*STRB*U*SIN(PSIW)*SIN(PSIW)
  530 CONTINUE
```

```
      VOL(I)=VCVD*AD2*0.5*(TAMX2-SIN2L-2.0*PSIW+SIN(2.0*PSIW))
      DIS(I)=(AD*(COS(PSIWW*PIC)-COS(PSIW))/(WKS*U*STRB))/12
  800 CONTINUE
  802 RL(I)=(P1(I)*P1(I))+(P2(I)*F2(I))
  804 RL(I)=SQRT(RL(I))
      EN(I)= P2(I)/VOL(I)
      ENMF(I)= PN2(I)/VOL(I)
  805 CONTINUE
      WRAP(I)=PI*AD2*SIN(PSIW)*SIN(PSIW)
      WRDPH(I)=AD*(1.0-COS(PSIW))
      IF(I.GT.1)GO TO 878
                  WRITE(6,3003)NOTE
 3003 FORMAT(1H1,47X40HCHRISTENSEN DIAMOND PRODUCTS COMPANY
     1/1H 5CX31HSINGLE DIAMOND CUTTING ANALYSIS
     2/1H0)5X1)A3,42X,27H F.C. APPL
      WRITE(6,3004) TELL
 3004 FORMAT(1H0 39X24A3,///)
  840 WRITE(6,24) SMX
  858 WRITE(6,13) OPC
  846 WRITE(6,32) AD
  848 WRITE(6,30) ALPD
  850 WRITE(6,34) SIGM
      WRITE(6,29) TAUI
  864 WRITE(6,18) U
  852 WRITE(6,6) VCVD
  854 WRITE(6,8)    (TEARTH(IX),IX=1,10)
  870 WRITE(6,17) ALD
  872 WRITE(6,19) SIGMA
      WRITE(6,26) SIGC
      WRITE(6,21) CD
      WRITE(6,38)WKS
  874 WRITE(6,4)
  878 WRITE(6,2)
      WRITE(6,36) PSIWI(I),P1(I),F2(I),RL(I),CUT(I),TAND(I),VOL(I),
     1WRAP(I),WRDPH(I),EN(I),DIS(I)
  882 CONTINUE
      IF(PSIWI(I).LT.(PSIMAX-DELPSI))GO TO 840
  900 CONTINUE
      GO TO 45
 1467 STOP
      END

$ENTRY
```

APPENDIX 2

EXPERIMENTAL DATA

Run No.	Z	Y	X	Rock Diameter (in)	Diamond Wear Area (10^{-4} in^2) (Profile)	(Plan)
1	14	3.0	2.2	7.293		
2	19	219	217	7.283		
3	21	3.1	3.0	7.276		
4	25	3.5	3.6	7.267		
5	27	3.2	3.9	7.258		
6	21	2.2	2.8	7.249		
7	26	3.1	3.6	7.238		
8	27	3.2	3.5	7.230	6.600	4.51
9	32	4.6	5.4	7.220		
10	20	2.2	2.9	7.210		
11	33	4.2	4.2	7.197		
12	33	3.7	3.5	7.187		
13	31	3.1	4.1	7.179		
14	32	3.3	3.6	7.169		
15	32	3.9	3.6	7.158		
16	33	4.0	3.6	7.149	8.96	6.49
17	27	3.2	3.7	7.139		
18	31	3.4	5.7	7.129		
19	30	3.8	5.2	7.121		

EXPERIMENTAL DATA

Run No.	Z	Y	X	Rock Diameter (in)	Diamond Wear Area (10^{-4} in^2) (Profile)	Diamond Wear Area (10^{-4} in^2) (Plan)
20	34	4.4	5.7	7.113		
21	37	4.7	4.8	7.103		
22	35	4.5	4.6	7.091		
23	33	4.1	4.3	7.082		
24	37	4.4	4.9	7.063	10.86	8.56
25	31	3.8	2.9	7.053		
26	32	4.0	2.9	7.043		
27	33	4.4	4.5	7.034		
28	32	4.0	4.3	7.024		
29	41	4.2	4.8	7.014		
30	40	4.0	4.2	7.004		
31	41	4.0	4.1	6.995		
32	42	4.0	4.3	6.985	12.31	9.28
33	30	2.8	3.3	6.974		
34	40	5.0	5.0	6.967		
35	42	4.4	4.8	6.958		
36	42	4.6	4.6	6.948		
37	40	4.4	4.3	6.938		
38	42	4.8	4.6	6.928		
39	40	4.6	4.5	6.919		
40	44	5.0	4.7	6.909	13.39	9.72
41	52	5.6	5.7	6.899		

EXPERIMENTAL DATA

Run No.	Z	Y	X	Rock Diameter (in)	Diamond Wear Area (10^{-4} in^2) (Profile)	(Plan)
42	44	3.6	4.7	6.885		
43	44	4.9	4.2	6.876		
44	43	4.9	4.0	6.865		
45	45	5.0	4.5	6.855		
46	43	4.8	4.1	6.845		
47	44	4.9	4.4	6.835		
48	48	5.1	4.5	6.826	14.29	10.48
49	28	3.3	2.5	6.817		
50	41	4.4	3.5	6.809		
51	46	5.1	4.2	6.799		
52	45	5.0	3.9	6.790		
53	45	5.0	3.9	6.780		
54	46	4.9	3.9	6.771		
55	43	4.6	3.6	6.762		
56	49	4.9	3.9	6.752	15.22	11.35
57	23	2.6	2.4	6.742		
58	41	4.3	3.9	6.734		
59	53	5.4	5.1	6.727		
60	45	4.6	4.3	6.718		
61	55	5.9	5.6	6.709		
62	53	5.7	5.1	6.699		
63	53	5.8	5.0	6.690		

EXPERIMENTAL DATA

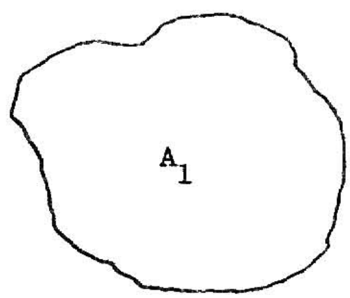
Run No.	Z	Y	X	Rock Diameter (in)	Diamond Wear Area (10^{-4} in^2) (Profile)	(Plan)
64	56	7.0	5.3	6.679	16.18	11.93
65	52	5.8	5.3	6.670		
66	51	6.8	4.6	6.661		
67	53	6.2	4.8	6.651		
68	55	6.6	5.1	6.641		
69	54	6.2	5.1	6.632		
70	55	5.3	5.0	6.621		
71	57	5.6	5.2	6.611		
72	53	5.2	4.7	6.602	16.92	12.87
73	55	5.8	5.3	6.593		
74	54	5.7	4.9	6.584		
75	53	5.7	4.8	6.574		
76	58	6.0	4.9	6.564		
77	61	6.2	5.1	6.555		
78	63	6.3	5.3	6.545		
79	59	6.0	4.6	6.534		
80	64	6.2	5.1	6.525	17.67	13.62
81	63	6.9	6.6	6.515		
82	57	6.1	5.1	6.506		
83	62	6.5	5.3	6.495		
84	63	6.5	5.2	6.484		
85	66	6.5	5.3	6.473		
86	65	6.7	5.4	6.463		

EXPERIMENTAL DATA

Run No.	Z	Y	X	Rock Diameter (in)	Diamond Wear Area (10^{-4} in^2) (Profile)	(Plan)
87	65	6.6	5.3	6.453		
88	64	6.6	5.2	6.444	18.18	14.47
89	66	6.9	6.7	6.433		
90	59	6.7	5.7	6.423		
91	59	6.3	5.3	6.412		
92	60	6.4	5.4	6.402		
93	59	6.3	5.3	6.392		
94	66	6.9	5.9	6.383		
95	67	6.9	5.3	6.371		
96	65	6.1	5.3	6.362	18.70	14.90
97	61	5.9	5.5	6.352		
98	61	5.9	5.5	6.343		
99	60	5.9	5.4	6.333		
100	62	6.2	5.4	6.324		
101	63	6.2	5.3	6.314		
102	65	6.5	5.3	6.304		
103	67	6.7	5.7	6.294		
104	61	6.1	4.8	6.284	19.50	15.43

APPENDIX 3

Diagram of Worn Diamond and Calculations

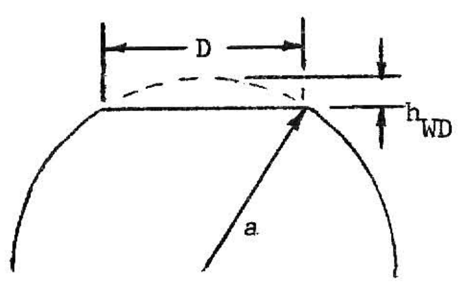


Area measured with a planimeter from Fig. 8a

$$A_1 = \pi (R_{eq})^2$$

$$R_{eq} = (A/\pi)^{1/2}$$

R_{eq} is the radius of a circle with area A_1 (Plan).



D is measured from Fig. 8b

$$D = 2\ R^*$$

$$R^* = D/2$$

R^* is the radius of a circle with area A_2 (Profile).

$$h_{WD} = a - (a^2 - R^2)^{1/2}$$

$$\text{Vol} = \frac{\pi}{3} (h_{WD})^2 (3a - h_{WD})$$

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AN EXPERIMENTAL INVESTIGATION OF THE CUTTING FORCES AND WEAR AREA OF A SINGLE DIAMOND

by

DON HELLAR

B.S., Kansas State University, 1970

AN ABSTRACT OF A MASTER'S THESIS

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Requirements for the Degree

MASTER OF SCIENCE

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ABSTRACT

The use of diamonds as a cutting tool material has a long history. With the increased use of diamonds for this purpose and the large costs that are involved, studies of the cutting action and wear of the diamond have become more important.

The purpose of this work, was to discover how a diamond wears under actual cutting conditions, and to compare these results with a previously developed theory on diamond wear. To do this, a diamond was used as a cutting tool for cutting a cylindrical piece of granite chucked in a lathe. The cutting forces were recorded on a specially built dynamometer.

The experimental results revealed that the relationship between diamond wear and cutting distance did not increase linearly, but progressed rapidly in the beginning and then slowed down. All experimental results were compared to the theory and found to be of similar trends but of slightly different magnitudes.