RI 8983

Bureau of Mines Report of Investigations/1985

Conical Bit Rotation as a Function of Selected Cutting Parameters

By Carl F. Wingquist, Bruce D. Hanson, Wallace W. Roepke, and Theodore A. Myren

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 8983

Conical Bit Rotation as a Function of Selected Cutting Parameters

By Carl F. Wingquist, Bruce D. Hanson, Wallace W. Roepke,
and Theodore A. Myren

UNITED STATES DEPARTMENT OF THE INTERIOR
Donald Paul Hodel, Secretary

BUREAU OF MINES
Robert C. Horton, Director

Library of Congress Cataloging in Publication Data:

Conical bit rotation as a function of selected cutting parameters.

(Report of investigations / United States Department of the Interior, Bureau of Mines ; 8983)

Bibliography: p. 13.

Supt. of Docs. no.: I 28.23: 8983.

1. Bits (Drilling and boring)—Testing. 2. Coal mining machinery—Testing. I. Wingquist, Carl F. II. Series: Report of investigations (United States. Bureau of Mines) ; 8983.

TN23.U43 [TN279] 622s [622'.23] 85-600120

CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

deg	degree	lbf	pound (force)
ft	foot	pct	percent
in	inch	s	second
in/s	inch per second	V	volt
lb	pound		

OTHER ABBREVIATIONS USED IN THIS REPORT

ANOVA	analysis of variance	F_Z	normal force
F_X	lateral force	T	moment about longitudinal axis of bit
F_Y	cutting force		

CONICAL BIT ROTATION AS A FUNCTION OF SELECTED CUTTING PARAMETERS

By Carl F. Wingquist,[1] Bruce D. Hanson,[2] Wallace W. Roepke,[3] and Theodore A. Myren[4]

ABSTRACT

The Bureau of Mines is engaged in research to evaluate the effects of cutter bit wear at coal mine faces. This paper addresses one element of conical bit wear, bit rotation. A discussion on mounting configuration and bit forces and their effects on rotation is presented. The effects on rotation and bit forces of bit attack angle, cutting depth, and skew are determined for two types of conical bits during linear cutting of sandstone-inclusive rock. The results indicate that a 10° negative skew angle and 35° attack angle produce the maximum rotation of 17.5° for each foot of cutting. Data on bit rotation and bit forces are presented in an appendix.

[1]Physicist.
[2]Physical scientist.
[3]Supervisory physical scientist.
[4]Mining engineering technician.
Twin Cities Research Center, Bureau of Mines, Minneapolis, MN.

INTRODUCTION

This laboratory study of conical bit rotation is part of an extensive ongoing Bureau research program on coal cutting technology in which the coal cutting system is being fully evaluated to determine those factors that affect the health and safety of the miners. The primary considerations are respirable dust generated by cutting and methane ignition due to frictional heating at the tool-mineral interface. It has been shown (1-4)[5] that bit wear increases the likelihood of methane ignition in gassy areas. It is also known that worn bits require a greater normal force (5) and thus tend to cut shallower, for a given machine thrust, than new bits. Since it has been demonstrated (6) that deep cutting lowers specific dust, it follows that bit wear leads to higher dust production. Although conical tools are intended to rotate freely so they will wear symmetrically, they commonly do not rotate effectively.

The primary purpose of this study was to investigate the relationship between conical bit rotation and bit attack angle, skew angle, bit type, cutting depth, and intercut spacing. Effective tool use requires that rotation of the bit occurs, particularly when cutting hard inclusive material such as sandstone and shale. Nonrotation results in rapid asymmetric wear of the tool tip and consequently, high normal force, shallow cutting, high specific dust, and premature tool failure. The information generated by this study should be of particular interest to tool and machine designers and mine operators using continuous mining machines since only by choosing tool mounting configurations and operating practices that enhance rotation can the full potential of the tool and machine be realized.

The initial step in this study was to identify those parameters felt to be relevant to bit rotation and then create a factorial experimental design or test plan based on those parameters. Cutting tests were then performed in which measurements of bit rotation and bit force were taken for each test condition. The resulting data were analyzed to determine the degree to which each parameter influenced rotation and bit forces. Additional tests, based on a central composite design, were carried out to provide a basis for predicting rotation.

ACKNOWLEDGEMENT

The authors wish to acknowledge Kennametal, Inc., of Latrobe, PA, for assistance in planning the testing and for providing the cutting tools used in the study.

BIT FORCE AND BIT ANGLE NOMENCLATURE AND DEFINITIONS

During cutting tests, bit forces were measured in three mutually perpendicular directions defined in reference to a rectangular (X,Y,Z) coordinate system oriented so that the XY plane is parallel to the sample cutting face with the Y axis parallel to the direction of cutting. These forces, which are named lateral force (F_X), cutting force (F_Y), and normal force (F_Z), are shown in figure 1 and are reported in pound-force (lbf) in this paper.

The attack and skew angles used to describe the mounting configuration of the bit are shown in figure 1 and defined in reference to the rectangular (X,Y,Z) coordinate system. The attack angle (θ) ranges from 30° to 50° and is defined as the angle between the longitudinal axis of the bit and the projection of the longitudinal axis into the XZ plane. The skew angle (ϕ) ranges from -10° to +10°

[5]Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

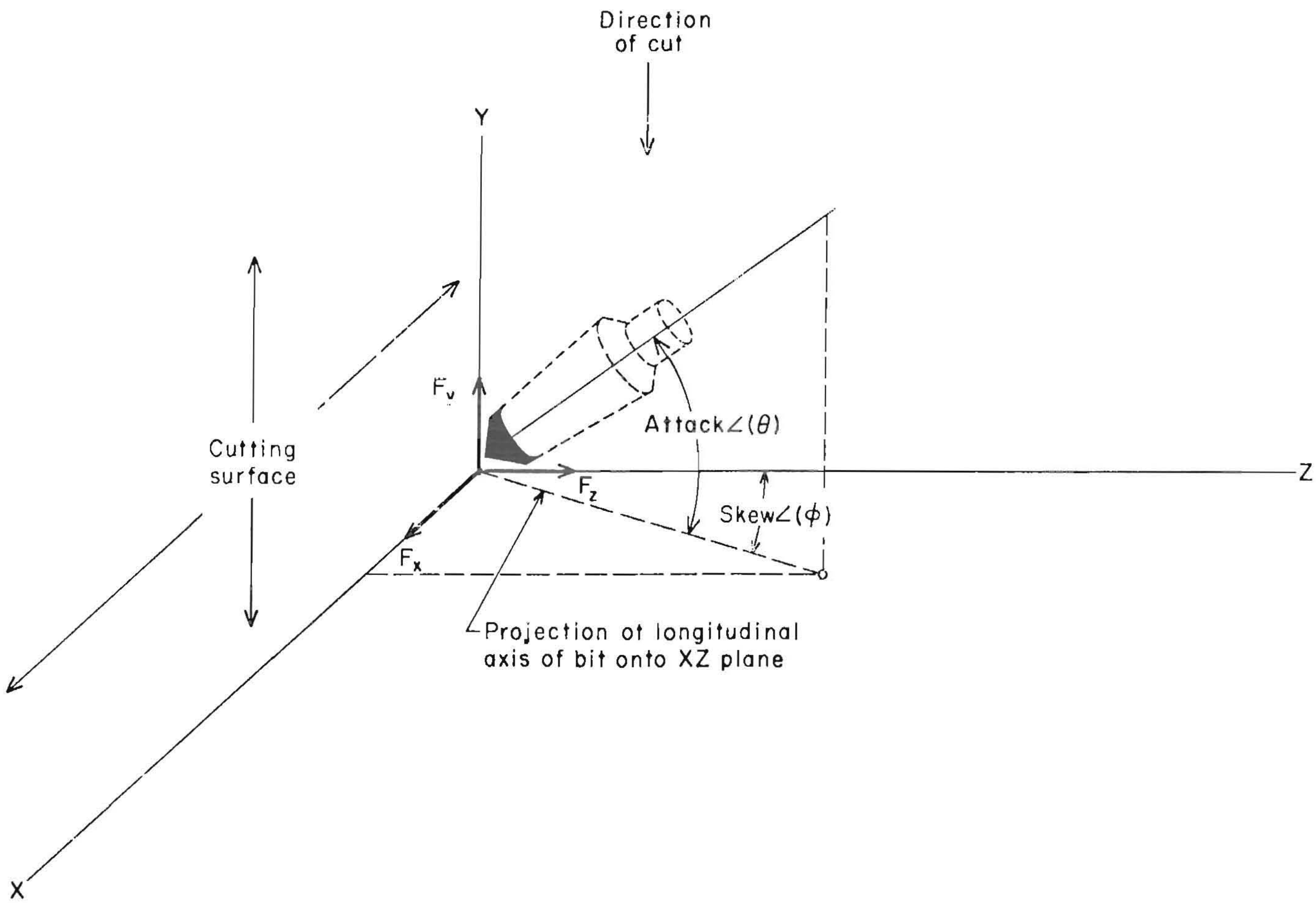

FIGURE 1. - Bit forces and attack and skew angles shown in reference to coordinate system.

and is defined as the angle between the projection of the longitudinal axis of the bit onto the XZ plane and the Z axis. Stated another way, if the longitudinal axis of the bit passes through the origin and point P (X,Y,Z), then the attack angle is given by

$$\Theta = \arc\sin \frac{Y}{(X^2+Y^2+Z^2)^{1/2}}.$$

The skew angle is given by

$$\phi = \arc\tan \frac{X}{Z}.$$

Skew is regarded as negative or positive depending on whether the bit is inclined away from or toward the uncut material respectively, as shown in figure 2.

CUTTING-INDUCED BIT ROTATION

Although an analysis of the mechanics of bit rotation is beyond the scope of this paper, it is obvious that if a bit is to rotate, a moment, or torque, about the longitudinal or rotational axis of the bit must be applied. Referring to figure 3, it can be seen that such a moment results when an unbalanced or net lateral force is present. To simplify illustration of the concept, the lateral force, F_X, is assumed to be applied at a single point on the tip of the bit. An unbalanced lateral force is generally a result of "asymmetrical" employment of the cutting tool such as nonzero bit skew or interactive cutting (in which the breakout zones of neighboring cuts overlap). The frictional force resulting

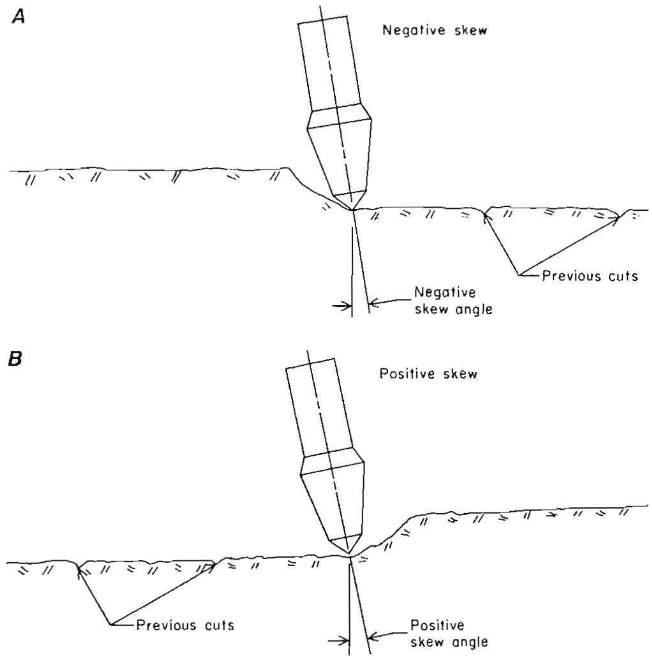

FIGURE 2. - Top view of bit showing (*A*) negative skew and (*B*) positive skew.

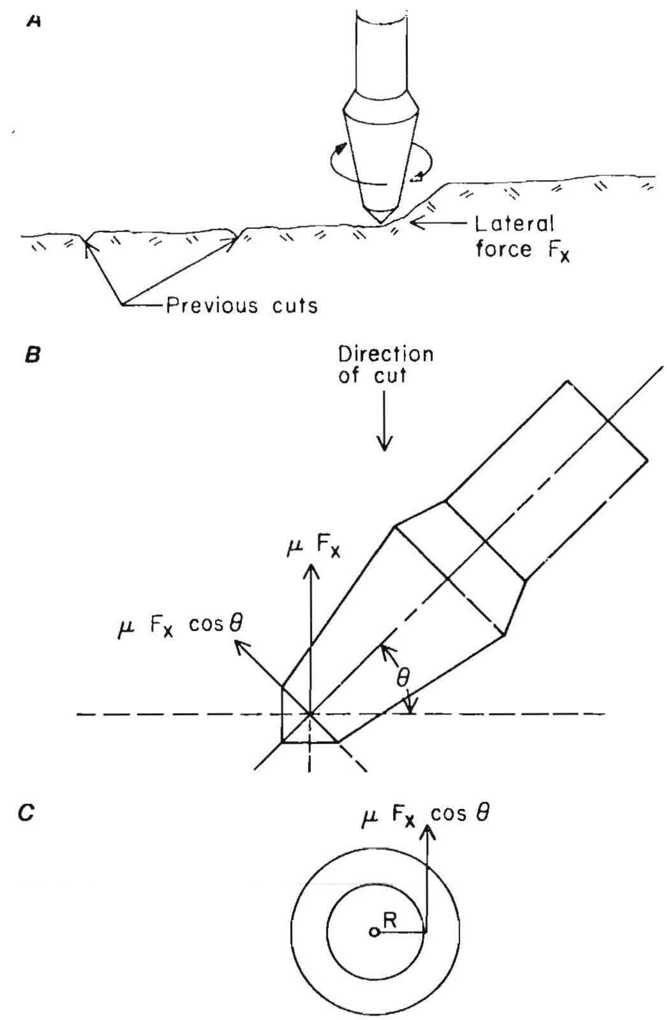

FIGURE 3. - Generation of rotational moment. *A*, Top view of bit showing application of lateral force; *B*, side view of bit showing frictional force and its component perpendicular to axis of rotation; *C*, end view of bit showing moment about rotational axis.

from the bit sliding against the rock is given by μF_x, where μ is the coefficient of friction between rock and steel. This force is directed opposite to the direction of cut. The component of this force acting at right angles to the longitudinal axis of the bit is given by $\mu F_x \cos \Theta$, when Θ is the angle of attack. The torque (T) or moment about the axis of rotation is thus given by $T = R\mu F_x \cos \Theta$.

The quantity R is the moment arm or the perpendicular distance in inches from the axis of rotation to the line of action of the force $\mu F_x \cos \Theta$.

It follows from the above analysis that the direction of rotation is dependent on the direction of the net lateral force. Thus, as shown in figure 3*A*, a positive lateral force (directed to the left) produces a negative (counterclockwise) rotation.

The above equation suggests that cutting with high lateral force and low angles of attack will insure rotation; however, the frictional binding that occurs due to high moments at the rock-bit and bit-holder interfaces resists rotation. For rotation to occur, it is necessary for the moment (T) to overcome frictional binding, and it was the primary objective of this study to identify which modes of cutting favor the generation of a rotational moment while maintaining reasonable cutting and normal forces and minimal binding.

It is anticipated that future work will include an analysis of the mechanics of bit rotation to establish the relationships between rotational moment, binding friction, and bit forces for various bit mounting configurations. Fast Fourier transforms of the bit force data will be studied to determine if any correlation exists between the frequency and amplitude of bit force fluctuation and rotation.

EXPERIMENTAL DESIGN

The experimental test plan was divided into two phases. First, a full factorial experiment was run using bit type, attack angle, skew angle, cut depth, and spacing as the independent variables. Each of the five variables was run at two levels (table 1). The two bits used are shown in figure 4. For each test, the amount of rotation per foot of cut and the lateral, cutting, and normal forces were measured. Standard analysis of variance (ANOVA) techniques were used to determine the significance of the five independent variables. The second phase of the test plan was to develop a central composite design, dropping any variables not showing any significant effects. The central composite design allows quantitative analysis of the relationships between the variables. A central composite design is composed of a factorial portion and an axial portion. Bit type did not affect any of the four dependent variables and was not included in the central composite design. The arrangement of the remaining four independent variables is shown in table 2. A more detailed explanation of both the factorial and the central composite experiments is found in appendix A.

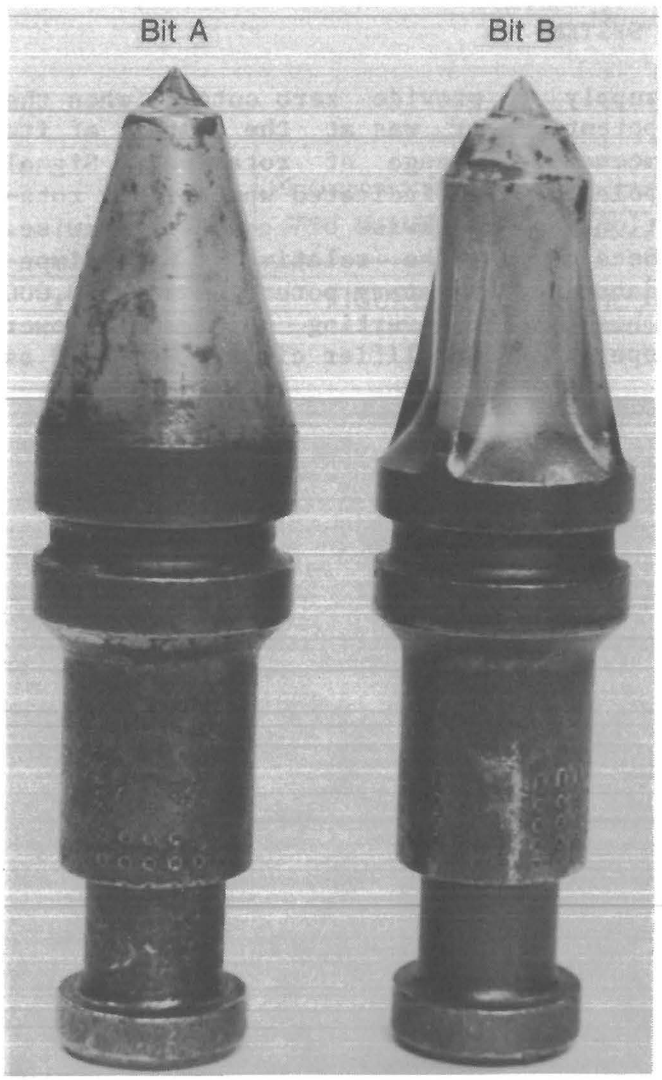

FIGURE 4. - Bit types tested. Both bits are approximately 5 in long.

TABLE 1. - Values of independent variables for factorial experiment

Bit type	Attack angle, deg	Skew angle, deg	Cut depth, in	Spacing, in
A	35	-10	0.25	0.50
B	45	+10	.50	1.00

TABLE 2. - Values of independent variables for central composite experiment

Attack angle, deg	Skew angle, deg	Cut depth, in	Spacing, in
FACTORIAL PORTION[1]			
35	-5	0.25	0.50
45	+5	.50	1.00
AXIAL PORTION			
40	0	0.375	0.75
30	0	.375	.75
50	0	.375	.75
40	-10	.375	.75
40	+10	.375	.75
40	0	.125	.75
40	0	.625	.75
40	0	.375	.25
40	0	.375	1.25

[1]All 16 possible combinations were run.

CUTTING SYSTEM

The modified Rockford model SA vertical slotter that was used to perform the cutting tests is shown in figure 5. Cutting speed is variable between 5 and 20 in/s with a maximum force capability of 11,000 lbf. The lateral motion of the worktable is synchronized with the vertical movement of the cutter ram so that crossfeed of a preset distance occurs between cuts. The crossfeed increment (distance between cuts) can be adjusted from 1/8 in to 2 in. The sample holder, into which the three-axis force dynamometer is incorporated, was designed specifically to hold the 1-ft cube rock samples used for these tests. The worktable is infed toward the cutter to obtain the desired depth of cut. The cutter ram, after engagement, cycles up and down vertically, producing a linear cut in the sample with each downstroke, with the bit retracting on the upstroke. A complete set of tool holders was designed and fabricated in-house to provide the several attack and skew angles required for the tests.

MEASUREMENT SYSTEM

A schematic representation of the measurement system is shown in figure 6.

Bit rotation was measured with a multiturn, low-torque rotary potentiometer, mechanically connected by a flexible coupling, to a 1/4-in shaft extending from the rear of the bit as shown in figure 7. Potentiometer excitation was supplied by a dual-voltage (±18 V dc) power supply to provide zero output when the potentiometer was at the center of its mechanical range of rotation. Signal polarity then indicated whether net rotation was clockwise or counterclockwise. Because of the relatively high impedance of the rotary potentiometer (10,000 ohms), a noninverting voltage follower operational-amplifier circuit was used as

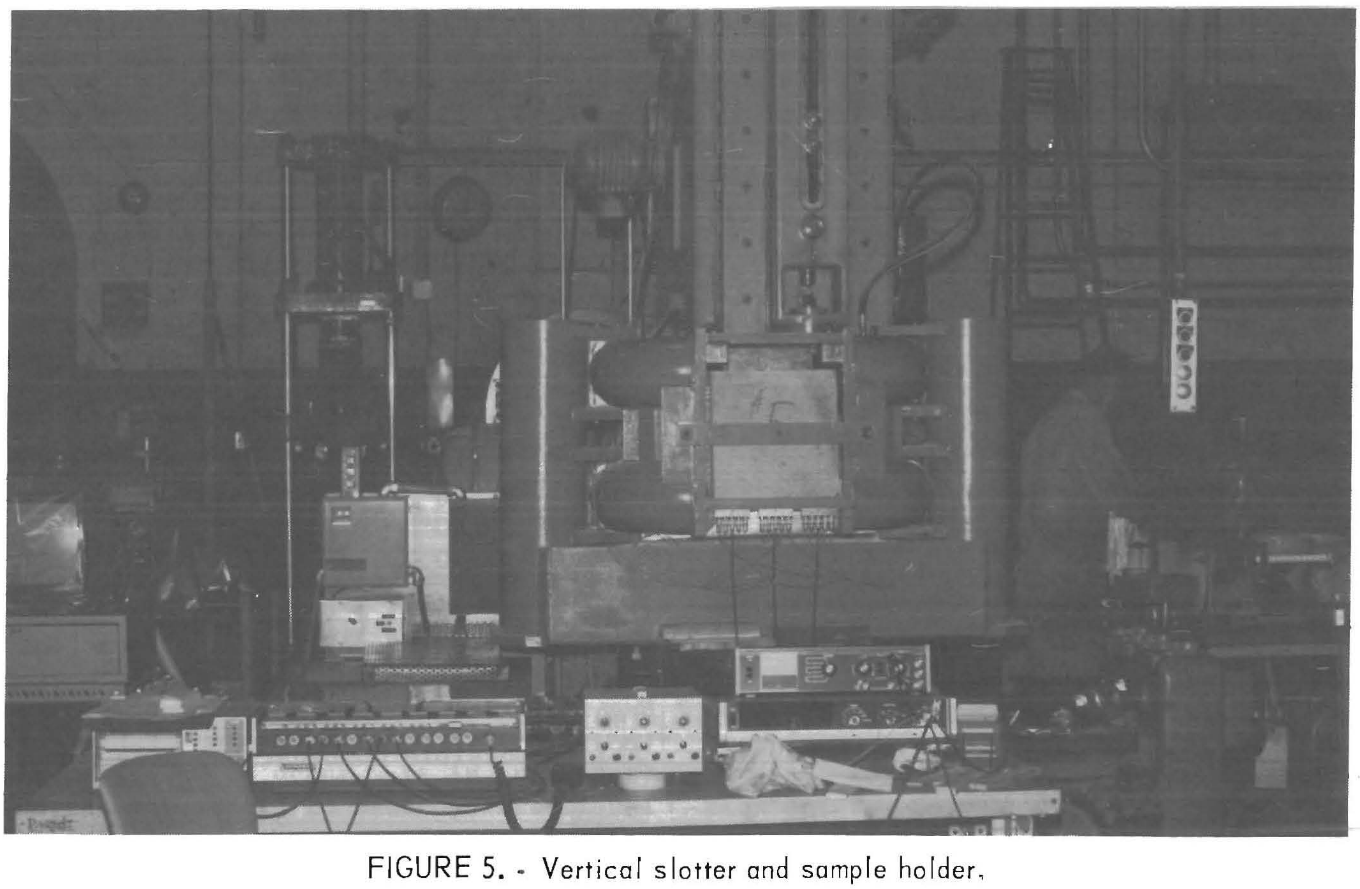

FIGURE 5. - Vertical slotter and sample holder.

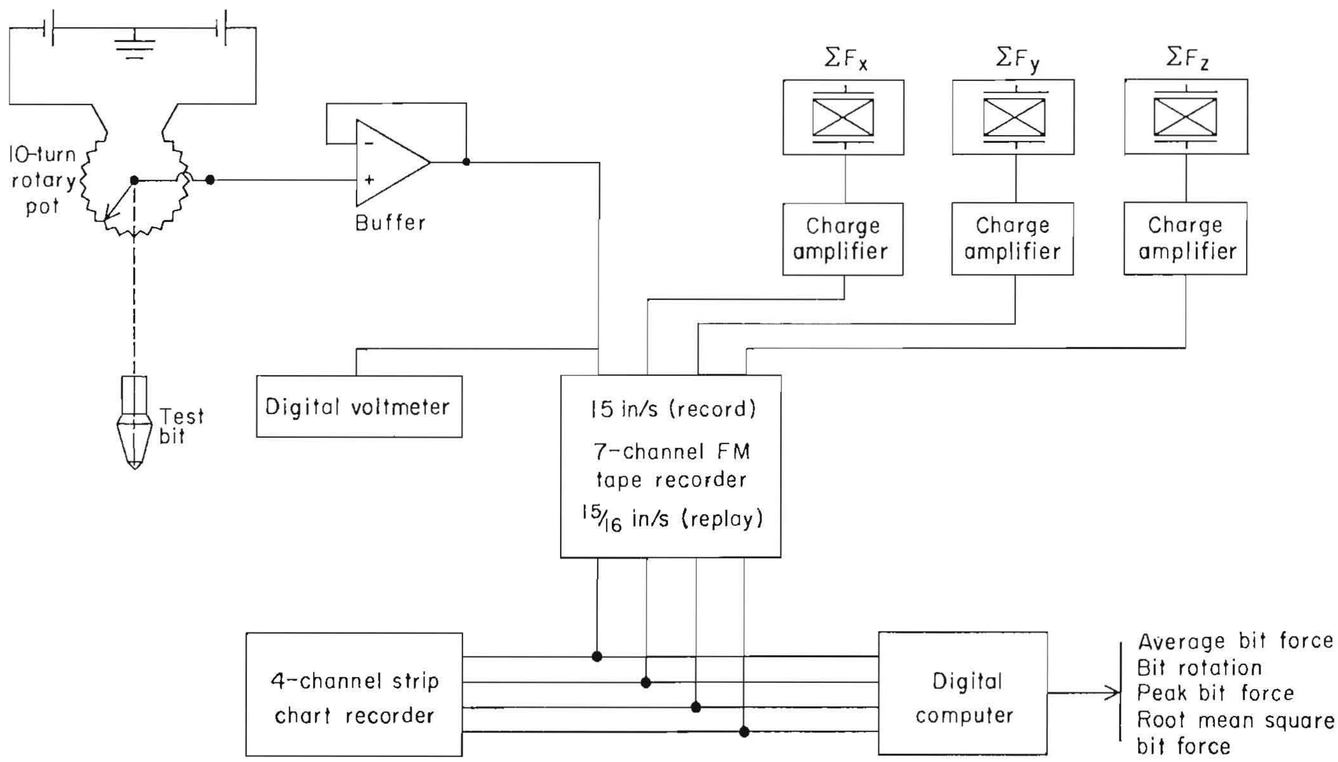

FIGURE 6. - Schematic diagram of measurement system.

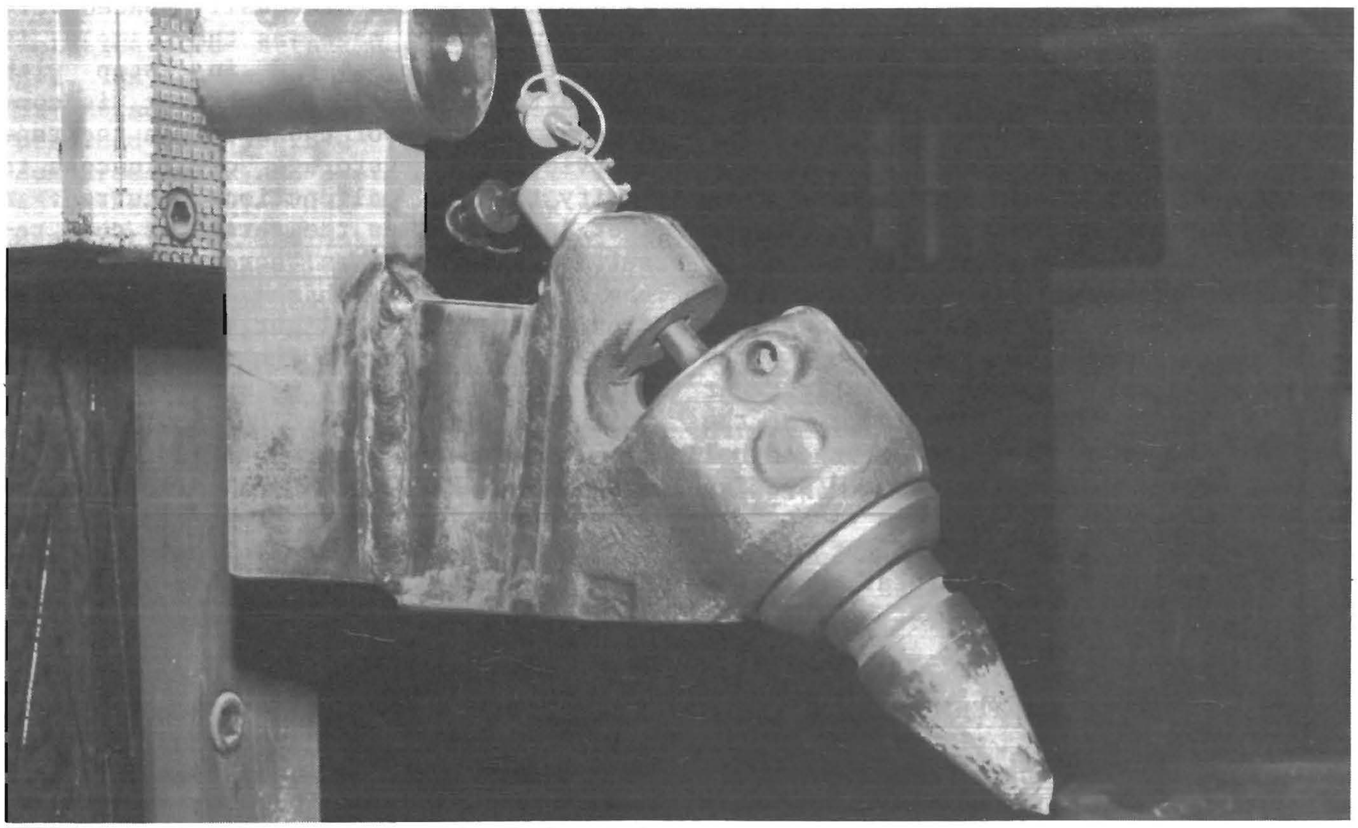

FIGURE 7. - Bit, holder, and rotary potentiometer.

a buffer between the potentiometer and the multichannel magnetic tape recorder used to record rotation and bit force signals. A digital voltmeter was used to monitor the rotation signal while the test was in progress.

Bit forces were measured in three mutually perpendicular directions. The sample holder was coupled to the worktable of the cutter machine through four three-axis piezoelectric load cells. The four outputs for each axis were connected in parallel to the input of a charge amplifier. A multichannel FM magnetic tape recorder was used to record the analog signals from the rotation and force measurement systems. Periodically, as the testing progressed, the tape was played into a four-channel strip chart recorder to produce a hard copy of the data for visual inspection and analysis. Additional processing and analysis were accomplished by the cutting laboratory computer system.

SAMPLE MATERIAL

The rock samples used for these cutting tests were cut from the Berea Sandstone Formation near Cleveland, OH. This rock is abrasive (78 pct quartz) with a compressive strength of 4,200 psi and is typical of inclusive rock encountered in coal cutting; such rock is the primary agent of bit wear rather than the coal, which causes minimal wear.

EXPERIMENTAL PROCEDURE

A tool holder and new bit are installed using the attack angle, skew angle, and bit type required for the particular test. The rock sample is placed in the sample holder and oriented so that the bedding planes of the rock are parallel to the direction of cutting but perpendicular to the Z axis (normal force direction). After the sample is securely clamped in place, a series of shallow interactive conditioning cuts are made on the smooth saw-cut surface. This trues up the cutting surface of the sample so it is parallel with the direction of crossfeed and also provides a rougher (more natural) test surface. The table is infed to produce the desired cut depth and moved laterally so that the first cut will occur at the extreme edge of the sample. The cross-feed increment control is then adjusted for the desired spacing between cuts, and the bit is rotated in its holder until a zero output is obtained from the multiturn rotary potentiometer. A voice announcement of the test number and test conditions is placed on one channel of the tape recorder at playback speed (3-3/4 in/s). After the recorder is brought up to data recording speed (15 in/s), the cutter ram is engaged and a series of equally spaced vertical cuts are made as the sample is automatically cross-fed in step with the cutter ram. After each test is completed, samples of the data on the tape are viewed on a storage oscilloscope to verify that no malfunctions occurred. A test is defined as the series of cuts resulting from one pass across the face of the sample. Although the wear resulting from one test is slight, a new bit is used for each test. The number of cuts in the test depends on the spacing required between cuts. The cutting speed on all tests was limited to 12 in/s since faster speeds would not allow sufficient time for sample crossfeed. Figure 8 shows a test sample following a test. The test results are given in tables A-1 and A-2 (appendix A).

DISCUSSION OF RESULTS

FACTORIAL EXPERIMENT

Bit type was the only independent variable that did not show any significant effect on any of the dependent variables. The other four affected at least two of four dependent variables measured. Tables 3-6 show the ANOVA results for rotation, cutting force, normal force, and lateral force. The two factors affecting

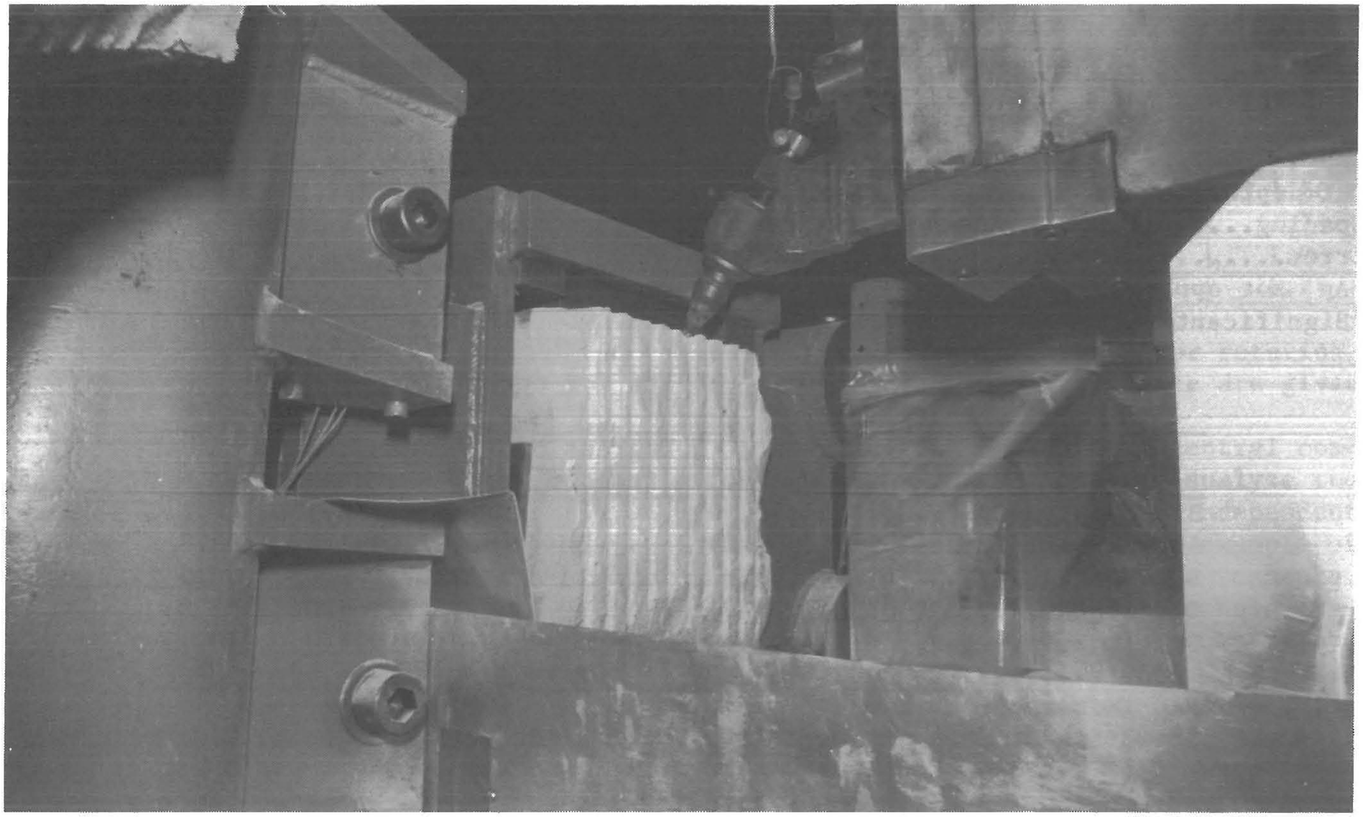

FIGURE 8. - Test sample after test.

rotation were attack angle and skew angle. As can be seen in table 7, using a 35° attack angle and a -10° skew angle produced an average rotation of 8.4°, compared with an average of 2.1° for a 45° attack angle and a +10° skew angle. Examination of the data in tables A-1 and A-2 confirms that the direction of rotation is determined by the direction of the lateral force. Both cutting force and normal force were affected by attack angle, skew angle, cut depth, and spacing. As expected, both forces increased with increasing cut depth and increasing spacing. Table 7 shows how these forces were affected by attack angle and skew angle. The force values at the 35° attack angle and -10° skew angle combination (maximum rotation) are slightly lower than those at the 45° attack angle and +10° skew angle combination (minimum rotation). Lateral force was affected by attack angle, skew angle, cut depth, and spacing. Lateral force increased with increasing cut depth and decreased with increasing spacing.

TABLE 3. - ANOVA results for rotation

	Sum of squares	Degrees of freedom	Mean square	F-value
Bit type.......	18.907	1	18.907	0.02
Attack angle...	144.554	1	144.554	[1]8.14
Skew angle.....	352.669	1	352.669	[1]19.85
Cut depth......	.637	1	.637	.04
Spacing........	1.817	1	1.817	.10
Error..........	1,225.722	69	17.764	NAp

NAp Not applicable.
[1]Significant at the 99-pct level of confidence.

TABLE 4. - ANOVA results for cutting force

	Sum of squares	Degrees of freedom	Mean square	F-value
Bit type	52.0	1	52.0	0.005
Attack angle	1,185,036.0	1	1,185,036.0	[1]107.6
Skew angle	882,428.0	1	882,428.0	[1]80.1
Cut depth	2,166,604.0	1	2,166,604.0	[1]196.6
Spacing	173,400.0	1	173,400.0	[1]15.7
Error	760,228.0	69	11,017.8	NAp

NAp Not applicable.
[1]Significant at the 99-pct level of confidence.

TABLE 5. - ANOVA results for normal force

	Sum of squares	Degrees of freedom	Mean square	F-value
Bit type	1,952.0	1	1,952.0	0.1
Attack angle	2,072,992.0	1	2,072,992.0	[1]155.8
Skew angle	1,395,632.0	1	1,395,632.0	[1]104.9
Cut depth	2,247,568.0	1	2,247,568.0	[1]168.9
Spacing	134,024.0	1	134,024.0	[1]10.1
Error	918,120.0	69	13,306.1	NAp

NAp Not applicable.
[1]Significant at the 95-pct level of confidence.

TABLE 6. - ANOVA results for lateral force

	Sum of squares	Degrees of freedom	Mean square	F-value
Bit type	14,876.0	1	14,876.0	2.0
Attack angle	28,394.0	1	28,394.0	[1]3.8
Skew angle	829,746.0	1	829,746.0	[2]112.1
Cut depth	1,406,261.0	1	1,406,261.0	[2]190.1
Spacing	206,370.0	1	206,370.0	[2]27.9
Error	510,439.0	69	7,397.7	NAp

NAp Not applicable.
[1]Significant at the 95-pct level of confidence.
[2]Significant at the 99-pct level of confidence.

TABLE 7. - Factorial experiment results

	Attack angle			
	35°		45°	
Skew angle	-10°	+10°	-10°	+10°
Rotation[1] ... deg	8.4	5.9	7.2	2.1
Force, lbf:				
Cutting	588	368	782	618
Normal	672	392	927	725
Lateral	363	152	372	211

[1]Per 12-in cut (absolute value).

NOTE.--The values presented are averaged over all levels of spacing and cut depth.

CENTRAL COMPOSITE EXPERIMENT

The central composite design allows a determination of the functional relationship between the variables of interest. The form of that relationship is

$$Y = A_o + \sum_{i=1}^{4} (A_i X_i + A_{ii} X_i^2)$$

$$+ \sum_{i=1}^{3} \sum_{j=i+1}^{4} A_{ij} X_i X_j$$

where Y = dependent variable (i.e., rotation),

X_i = independent variables (i.e., attack angle),

and A_i, A_{ii}, and A_{ij} = coefficients.

Computational procedures required the coding of the independent variables. The X_i's in the above equation are the coded values. Table 8 gives the relationship betwen the X_i's and the four independent variables. A sample calculation using the model is given in appendix B.

Results for the central composite design are given in tables 9-12. With the exception of lateral force, the model presented above gave a reasonable fit to the data. The coefficients for rotation, cutting force, and normal force are given in table 13.

As previously stated, the central composite model can be used to analyze the relationships between the independent variables. Table 14 shows an example of this type of analysis. In the example, attack angle and cut depth are held constant at 35° and 0.5 in, respectively. As shown in the table, with the skew angle at -10°, increasing the spacing causes an increase in rotation. However, with the skew angle at +10° increasing spacing results in a decrease in rotation. This brief analysis illustrates the complex nature of the interactions between the variables.

It should be noted that the model is not valid outside the limits of the factorial portion of the experiment (table 2).

TABLE 8. - Coding values for X_i's

X_i	Attack angle, deg	Skew angle, deg	Cut depth, in	Spacing, in
-2	30	-10	0.125	0.25
-1	35	-5	.25	.50
0	40	0	.375	.75
1	45	5	.50	1.00
2	50	10	.625	1.25

TABLE 9. - ANOVA for rotation - central composite design

	Sum of squares	Degrees of freedom	Mean square	F-value
1st-order terms..........	125.30	4	31.33	[1]20.06
2d-order terms...........	129.20	10	12.92	[2]8.27
Lack of fit..............	76.21	10	7.62	[3]4.88
Blocks...................	50.71	2	25.36	[1]16.24
Error....................	4.68	3	1.56	NAp

NAp Not applicable.
[1]Significant at the 95-pct level of confidence.
[2]Significant at the 90-pct level of confidence.
[3]Not significant at the 90-pct level of confidence.

TABLE 10. - ANOVA for cutting force - central composite design

	Sum of squares	Degrees of freedom	Mean square	F-value
1st-order terms....................	591,857.0	4	147,964.3	[1]47.14
2d-order terms.....................	161,835.2	10	16,183.5	[2]5.16
Lack of fit........................	67,432.8	10	6,743.3	[3]2.15
Blocks.............................	545.0	2	272.5	[3].09
Error..............................	9,417.0	3	3,139.0	NAp

NAp Not applicable.
[1]Significant at the 95-pct level of confidence.
[2]Significant at the 90-pct level of confidence.
[3]Not significant at the 75-pct level of confidence.

TABLE 11. - ANOVA for normal force - central composite design

	Sum of squares	Degrees of freedom	Mean square	F-value
1st-order terms....	611,186.4	4	152,796.6	[1]40.76
2d-order terms.....	247,837.6	10	24,783.8	[2]6.61
Lack of fit........	114,929.8	10	11,493.0	[3]3.07
Blocks.............	216.8	2	108.4	[4].03
Error..............	11,245.5	3	3,748.5	NAp

NAp Not applicable.
[1]Significant at the 95-pct level of confidence.
[2]Significant at the 90-pct level of confidence.
[3]Not significant at the 90-pct level of confidence.
[4]Not significant at the 75-pct level of confidence.

TABLE 12. - ANOVA for lateral force - central composite design

	Sum of squares	Degrees of freedom	Mean square	F-value
1st-order terms....	695,153.4	4	173,788.4	[1]2.04
2d-order terms.....	369,304.9	10	36,930.5	[1].43
Lack of fit........	130,523.7	10	13,052.4	[1].15
Blocks.............	14,625.8	2	7,312.9	[1].9
Error..............	255,565.5	3	85,188.5	NAp

NAp Not applicable.
[1]Not significant at the 75-pct level of confidence.

TABLE 13. - Coefficients from central composite design analysis

Coeff[1]	Rotation	Cutting force	Normal force	Coeff[1]	Rotation	Cutting force	Normal force
A_0	1.9167	429.3333	397.1667	A_{44}	0.2229	-6.2292	-10.3438
A_1	-1.3833	90.4167	118.1250	A_{12}	1.3750	36.6250	39.1875
A_2	-1.7250	-28.4167	-37.8750	A_{13}	-.0625	-38.5000	-39.6875
A_3	.0333	124.5000	100.3750	A_{14}	-.6500	7.0000	2.9375
A_4	.5750	13.3333	-1.7083	A_{23}	.9625	-13.7500	-24.3125
A_{11}	.2604	40.0208	54.2813	A_{24}	-1.7500	55.0000	64.0625
A_{22}	.6229	1.5208	6.4063	A_{34}	-1.0125	-29.8750	-41.8125
A_{33}	.1729	-4.4792	-7.3438				

[1]In the subscripts to the coefficients, 1 = attack angle, 2 = skew angle, 3 = depth, and 4 = spacing.

TABLE 14. - Predicted values for rotation

	Rotation, deg/ft of cut	
Skew angle......	-10°	+10°
0.5 in spacing..	4.9	4.1
1.0 in spacing..	8.8	1.0

SUMMARY

The results of this work show that rotation of conical bits is chiefly affected by the attack angle and the skew angle of the bit. A 35° attack angle produced more rotation than a 45° attack angle in both the factorial and the central composite experiments. Similarly, a negative skew angle produced more rotation than a positive skew angle. The central composite experiment also indicated that maximum rotation is obtained with a 0.25-in cut depth and 1.00-in spacing when the attack angle and skew angle are set at their most efficient levels. The direction of rotation depends on the sign or direction of the net lateral force. The cutting and normal forces for the maximum rotation conditions are 301 and 294 lb, respectively. Maximum rotation is obtained at reasonable levels of cutting and normal force.

REFERENCES

1. Larson, D. A., V. W. Dellorfano, C. F. Wingquist, and W. W. Roepke. Preliminary Evaluation of Bit Impact Ignitions of Methane Using a Drum-Type Cutting Head. BuMines RI 8755, 1983, 23 pp.

2. Roepke, W. W., and B. D. Hanson. Testing Modified Coal-Cutting Bit Designs for Reduced Energy, Dust, and Incendivity. BuMines RI 8801, 1983, 31 pp.

3. Hanson, B. D. Cutting Parameters Affecting the Ignition Potential of Conical Bits. BuMines RI 8820, 1983, 14 pp.

4. Roepke, W. W., and B. D. Hanson. Bit Ignition Potential With Worn Carbide Tips. BuMines TPR 121, 1983, 7 pp.

5. _____. Effect of Asymmetric Wear of Point Attack Bits on Coal-Cutting Parameters and Primary Dust Generation. BuMines RI 8761, 1983, 16 pp.

6. Black, S., R. L. Schmidt, B. V. Johnson, and B. Banerjee. Effect of Continuous Miner Parameters on the Generation of Respirable Dust. Min. Cong. J., v. 64, No. 4, 1978, pp. 19-25.

APPENDIX A

For the factorial segment of the experiment, a full 2^5 factorial design with block confounding was used. Block confounding was necessary because all 32 combinations could not be run on a single sandstone block. The factorial was divided into four blocks using the bit × attack angle × skew angle, the bit × spacing × depth, and the attack angle × skew angle × spacing × depth interactions as confounded effects. Both the order of the eight tests on each block and the order of each block were randomized.

The central composite design also had to be run in different blocks. The factorial portion was run on two blocks using the attack angle × skew angle × spacing × depth interaction as the confounded effect. The axial portion was run on a third block. Two center points were run on each of the three blocks.

The data for both the full factorial and the central composite designs are shown in tables A-1 and A-2.

TABLE A-1. - Test results for factorial experiment

ATTACK ANGLE, DEG	SKEW ANGLE, DEG	CUT DEPTH, IN	SPACING, IN	BLOCK NO.	ROTATION, DEG	AVERAGE FORCE, LB			RMS FORCE, LB			PEAK FORCE, LB		
						LATERAL	CUTTING	NORMAL	LATERAL	CUTTING	NORMAL	LATERAL	CUTTING	NORMAL
BIT TYPE A														
35	-10	0.25	0.50	1	13.9	-349	574	678	389	643	754	-913	1420	1646
					2.9	-172	336	375	228	402	476	-716	1042	1221
					4.0	-284	487	604	336	551	660	-811	1234	1378
			1.00	3	17.4	-195	492	588	266	611	725	-820	1740	1859
					22.6	-160	390	403	229	478	508	-673	1294	1411
					12.5	-190	375	453	286	463	555	-861	1263	1476
		0.50	0.50	3	3.5	-688	900	1069	732	959	1116	-1406	1840	1924
					2.5	-528	811	748	586	894	813	-1251	2046	1688
					4.3	-446	612	769	488	693	829	-1060	1573	1632
			1.00	1	1.2	-658	984	1151	712	1084	1225	-1406	2275	2377
					3.0	-308	601	548	377	715	641	-929	1878	1525
					4.5	-441	685	848	504	783	906	-1237	1992	1886
	+10	0.25	0.50	2	-5.5	96	162	252	151	243	316	483	804	986
					-4.8	102	233	236	172	303	299	596	998	873
					-4.1	96	248	280	180	323	353	393	1091	1115
			1.00	4	8.6	-53	380	444	146	535	574	-318	1702	1678
					2.8	-7	274	247	125	374	352	-31	1291	1206
					3.2	-46	209	242	151	311	340	-159	1256	1206
		0.50	0.50	4	-19.5	305	440	537	391	540	597	932	1441	1357
					-6.3	279	419	338	363	521	419	1020	1586	1144
					-10.5	235	332	414	335	452	506	1044	1416	1329
			1.00	2	-8.3	163	394	543	268	583	635	896	1888	1752
					-4.0	251	592	498	355	795	630	1032	2473	2051
					-5.7	190	912	808	499	1123	949	671	3001	2484
45	-10	0.25	0.50	2	0.0	-164	497	700	206	567	787	-597	1396	1796
					4.1	-150	447	531	206	536	636	-673	1426	1631
					16.5	-374	825	940	409	889	998	-901	1804	1867
			1.00	4	7.8	-183	762	908	280	879	1009	-859	1977	2042
					6.3	-168	442	477	224	517	552	-633	1459	1293
					0.0	-161	416	535	220	495	626	-706	1451	1671
		0.50	0.50	4	12.0	-601	1019	1243	639	1085	1297	-1322	2057	2138
					13.4	-189	301	321	215	331	351	-518	698	725
					9.0	-449	679	823	491	768	884	-1098	1767	1770
			1.00	2	8.6	-428	872	1188	468	1000	1278	-1052	2570	2687
					10.8	-402	1119	1183	502	1271	1299	-1407	3101	2748
					15.0	-784	1350	1410	844	1478	1521	-1659	3206	2971
	+10	0.25	0.50	1	-1.1	157	383	498	254	486	614	816	1402	1722
					-1.2	84	229	247	176	306	345	756	1117	1267
					0.0	151	317	362	235	402	454	724	1334	1372
			1.00	3	2.4	-1	869	1075	240	1012	1204	-462	2047	2048
					1.0	19	507	581	159	604	686	81	1723	1909
					-2.1	-34	416	534	214	508	621	-376	1462	1554
		0.50	0.50	3	-4.9	556	936	1114	652	1040	1216	1516	2259	2423
					-3.2	420	723	735	570	841	899	1603	2021	2330
					-3.9	305	592	685	424	723	791	1123	1931	1965
			1.00	1	-4.3	253	1232	1531	505	1428	1688	1032	3406	3498
					-1.6	184	726	765	290	842	882	876	2228	2171
					0.0	118	725	924	336	905	1109	778	2654	2928

TABLE A-1. - Test results for factorial experiment--Continued

ATTACK ANGLE, DEG	SKEW ANGLE, DEG	CUT DEPTH, IN	SPACING, IN	BLOCK NO.	ROTATION, DEG	AVERAGE FORCE, LB LATERAL	AVERAGE FORCE, LB CUTTING	AVERAGE FORCE, LB NORMAL	RMS FORCE, LB LATERAL	RMS FORCE, LB CUTTING	RMS FORCE, LB NORMAL	PEAK FORCE, LB LATERAL	PEAK FORCE, LB CUTTING	PEAK FORCE, LB NORMAL
BIT TYPE B														
35	-10	0.25	0.50	4	9.6	-330	514	633	363	568	687	-880	1236	1448
					16.3	-227	428	442	283	483	516	-792	1109	1215
					17.3	-227	355	447	269	414	516	-711	1056	1238
			1.00	2	13.8	-191	322	452	236	398	532	-626	1084	1353
					10.8	-125	375	377	200	449	449	-721	1233	1134
					19.2	-201	496	568	292	603	682	-917	1662	1819
		0.50	0.50	2	1.3	-437	459	732	473	534	781	-994	1305	1479
					5.0	-490	730	754	557	827	842	-1277	1875	1793
					0.0	-822	1106	1292	860	1166	1343	-1554	2123	2275
			1.00	4	2.2	-568	890	1028	650	1027	1118	-1333	2378	2326
					8.3	-288	552	514	357	662	613	-1043	1829	1513
					5.5	-381	629	663	461	775	761	-1164	2175	1730
	+10	0.25	0.50	3	-4.7	165	310	360	240	392	437	732	1156	1129
					-3.9	78	207	212	165	288	305	465	994	1008
					-2.3	73	179	221	151	252	282	427	885	864
			1.00	1	7.0	-117	267	361	181	385	494	-588	1317	1596
					-2.2	42	218	198	127	290	273	454	985	951
					2.6	-17	219	258	153	316	329	-269	1206	1009
		0.50	0.50	1	-5.6	469	581	659	565	679	728	1360	1614	1623
					-7.6	284	412	351	366	524	443	1016	1581	1216
					-6.5	330	444	519	425	554	596	1145	1611	1415
			1.00	3	-4.0	54	558	634	362	726	734	358	2122	1907
					-4.7	143	432	345	261	615	475	775	2423	1511
					-6.4	48	403	453	262	604	565	260	2086	1794
45	-10	0.25	0.50	3	3.3	-407	883	1115	456	940	1176	-991	1782	2008
					7.3	-276	590	656	324	657	729	-744	1391	1523
					2.9	-216	427	579	267	500	691	-658	1259	1566
			1.00	1	1.2	-184	747	964	272	838	1051	-802	1946	2045
					1.9	-229	590	659	289	659	730	-777	1563	1633
					2.3	-156	676	879	263	762	956	-854	1910	1961
		0.50	0.50	1	6.0	-697	1123	1456	736	1183	1511	-1475	2128	2331
					3.1	-409	775	834	459	851	907	-994	1775	1732
					8.5	-585	963	1182	634	1032	1238	-1200	2113	2130
			1.00	3	18.1	-718	1337	1546	772	1437	1645	-1601	2840	2886
					7.6	-493	1026	1029	568	1157	1127	-1304	2979	2302
					8.2	-508	894	1093	565	993	1166	-1143	2518	2146
	+10	0.25	0.50	4	0.0	174	575	776	254	652	850	832	1519	1810
					0.0	115	353	413	195	420	512	767	1201	1508
					-1.5	150	316	425	247	408	520	799	1189	1422
			1.00	2	0.0	53	484	634	163	581	729	398	1591	1806
					1.0	-25	524	549	215	645	664	-576	1873	1713
					3.7	-191	725	887	324	829	982	-980	1939	1999
		0.50	0.50	2	-2.4	203	403	694	305	499	765	1022	1384	1777
					-7.6	385	645	572	486	781	677	1195	2211	1678
					-3.1	671	941	983	737	1031	1056	1349	2406	2092
			1.00	4	-2.2	425	1098	1210	550	1242	1308	1519	3009	2732
					-1.4	215	573	514	328	727	621	1068	2409	1667
					-2.1	180	542	694	338	728	832	859	2563	2282

TABLE A-2. - Test results for central composite design

ATTACK ANGLE, DEG	SKEW ANGLE, DEG	CUT DEPTH, IN	SPACING, IN	BLOCK NO.	ROTATION, DEG	AVERAGE FORCE,LB LATERAL	AVERAGE FORCE,LB CUTTING	AVERAGE FORCE,LB NORMAL	RMS FORCE,LB LATERAL	RMS FORCE,LB CUTTING	RMS FORCE,LB NORMAL	PEAK FORCE,LB LATERAL	PEAK FORCE,LB CUTTING	PEAK FORCE,LB NORMAL
35	-5	0.25	0.50	1	6.0	-140	262	268	189	315	333	-574	800	838
			1.00	2	16.6	-127	301	294	208	371	417	-733	1071	1391
		0.50	0.50		6.2	-373	648	598	418	719	667	-940	1564	1379
			1.00	1	11.6	-269	596	550	336	678	630	-934	1826	1482
	+5	0.25	0.50	2	-.5	56	139	121	105	185	169	354	764	589
			1.00	1	2.1	-5	221	191	102	291	257	-259	1003	891
		0.50	0.50		-7.7	336	503	446	389	576	508	893	1372	1117
			1.00	2	-.8	221	453	367	290	569	457	840	1859	1352
45	-5	0.25	0.50		2.5	-189	480	514	245	549	626	-724	1382	1644
			1.00	1	4.6	-152	351	351	188	400	405	-489	1090	1029
		0.50	0.50		1.7	-303	726	789	340	791	840	-742	1726	1636
			1.00	2	3.1	-261	503	454	308	588	522	-726	1621	1187
	+5	0.25	0.50	1	-.9	115	312	322	174	364	396	559	984	1128
			1.00	2	.2	91	634	716	161	725	803	608	1813	1965
		0.50	0.50		-3.0	323	524	496	367	576	559	772	1343	1261
			1.00	1	-.5	278	685	616	357	805	712	904	2101	1651
30	0	0.38	0.75	3	.4	155	323	255	220	417	335	818	1310	1012
50					1.3	214	862	961	336	960	1077	977	2252	2311
40	-10				3.5	-240	510	508	292	572	564	-705	1326	1204
	+10				1.1	168	367	325	258	479	452	870	1623	1474
	0	0.13			-.6	-23	152	144	68	193	189	-100	609	624
		0.63			.4	-373	677	579	427	761	629	-962	1945	1297
		0.38	0.25		0.0	241	365	356	279	406	398	653	875	654
			1.25		-1.4	142	450	343	239	585	462	798	1933	1457
			0.75	1	1.2	-224	477	442	271	542	496	-640	1376	1116
					-3.8	215	413	377	271	487	453	771	1343	1148
				2	-2.8	170	365	338	226	426	415	684	1253	1165
					1.3	-227	438	409	276	504	465	-701	1406	1198
				3	.9	-236	490	466	273	545	510	-607	1462	1068
					-1.5	165	393	351	222	470	428	616	1325	1223

APPENDIX B

The procedure to follow in using the empirical model on page 11 to predict rotation, normal force, or cutting force for a given attack angle, skew angle, cut depth, and spacing is illustrated by the following example: Given attack angle = 30°, skew angle = -5°, depth = 0.5 in, and spacing = 0.75 in, find rotation. First the condensed form of the equation

$$Y = A_o + \sum_{i=1}^{4} (A_i X_i + A_{ii} X_i^2) + \sum_{i=1}^{3} \sum_{j=i+1}^{4} A_{ij} X_i X_j$$

should be expanded to the form:

$$Y = A_o + A_1X_1 + A_{11}X_1^2 + A_2X_2 + A_{22}X_2^2 + A_3X_3 + A_{33}X_3^2 + A_4X_4 + A_{44}X_4^2$$

$$+ A_{12}X_1X_2 + A_{13}X_1X_3 + A_{14}X_1X_4 + A_{23}X_2X_3 + A_{24}X_2X_4 + A_{34}X_3X_4$$

where the subscripted A's are the coefficients from table 13 and X_1, X_2, X_3, and X_4 are the independent variables attack angle, skew angle, depth, and spacing respectively.

Next, using table 8, determine the coded values corresponding to each independent variable X_i. Thus for an attack angle of 30°, a skew angle of -5°, a cutting depth of 0.5 in, and a spacing of 0.75 in, the values of X_1, X_2, X_3, and X_4 are -2, -1, 1, and 0 respectively. Substitution of the coded values for the independent variables and the coefficients from the rotation column of table 13 into the expanded form of the equation yields

$$Y = 1.92 + (-1.38)(-2) + (0.26)(-2)^2 + (-1.72)(-1) + (0.62)(-1)^2 + (0.03)(1)$$

$$+ (0.17)(1)^2 + (0.58)(0) + (0.22)(0)^2 + (1.38)(-2)(-1) + (-0.06)(-2)(1)$$

$$+ (-0.65)(-2)(0) + (0.96)(-1)(1) + (-1.75)(-1)(0) + (-1.01)(1)(0)$$

or $Y = 10.18$ deg/ft.

☆U.S. GPO: 1985-505-019/20,105

INT.-BU.OF MINES,PGH.,PA. 28094