Preprint 02-136

DESIGN METHODOLOGY, TESTING AND EVALUATION OF A CONTINUOUS MINER CUTTERHEAD FOR DUST REDUCTION IN UNDERGROUND COAL MINING

B. Asbury and M. Cigla
Colorado Schl of Mines
Golden, CO

C. Balci
Istanbul Tech Univ
Istanbul

ABSTRACT

The Western Mining Resource Center (WMRC) at the Colorado School of Mines (CSM) received a grant from the National Institute for Occupational Safety and Health (NIOSH) to perform a study that will help reduce the amount of respirable dust generated from the cutting of coal. The study is based upon laboratory testing and field experience. This information is being used to develop a new cutterhead design in conjunction with Joy Mining Machinery. The new cutterhead design is being evaluated with existing computer models developed at CSM. The new continuous miner cutterhead will be tested at the Twenty Mile Coal Company's Foidal Creek Mine. Baseline testing with the current cutterhead will also be performed. This paper presents laboratory test results, design methodology, and test results performed to date.

BACKGROUND

A need to reduce the amount of respirable dust exists in the underground mining industry. Crippling and fatal diseases result from retention of coal dust in the lungs. These included coal workers pneumoconiosis (CWP, a.k.a Black Lung), progressive massive fibrosis (PMF), silicosis, and chronic obstructive pulmonary disease. In 1998 mine operators reported 224 cases of CWP and PMF (combined), 138 of which occurred among underground coal miners. In the same year 14 cases of silicosis were reported, 8 being from underground miners. These statistics do not include the occupational health of all coal miners, since the miners participate in the programs at their own discretion.

INTRODUCTION

In the United States, approximately 1/3 of annual coal production comes from underground mines. Almost all underground coal production is produced by continuous miners and longwall shearers. As mechanical mining technologies advance, more underground non-coal mining operations utilize mechanical methods for mining and development. The majority of respirable dust generated by mechanical miners is generated by material that is crushed directly under the individual bits/cutters on the cutterhead. Figure 1 shows the crush zone underneath a bit, and the resulting fractures in the rock that lead to production. Reducing the amount of dust generated reduces the amount of dust that can become airborne in the working area and pose a health hazard.

It is known that cutting geometry affects the amount of dust generated under an individual cutter/bit. These cutting geometry factors include bit tip angle, angle of attack, and bit penetration. Also, reducing the number of cutters engaging the rock, which results in an increase of bit spacing, can reduce the total amount of dust generated. These variables also have a major effect on production. A full scale test program has been performed to help quantify the effects of the different variables on dust generation as well as production. Field tests are planned to confirm the full scale laboratory cutting tests.

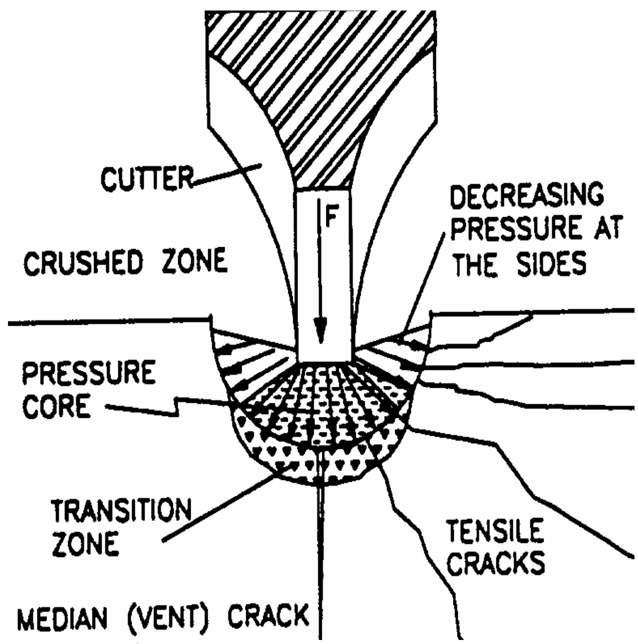

Figure 1: Crush zone, where dust is generated.

LINEAR CUTTING TEST PROGRAM

A full scale laboratory test program was performed to help quantify the effect of cutting geometry on the generation of respirable dust. This test program consisted of full scale cutting tests using different bit types at differing cutting geometries in a coal measure rock, a high silica sandstone. The Linear Cutting Machine (LCM) at the Colorado School of Mines was used for conducting the cutting tests. The LCM forces a large rock sample through an actual bit at a preset cutting geometry. After each pass of cutting tests, muck samples were collected to determine the relative percentages of respirable dust. The linear cutting tests also measure forces acting on the cutter to ensure that the bits are operating as they would on an actual excavator while providing an acceptable level of production. This full-scale testing eliminates the uncertainties of scaling and any unusual rock cutting behaviour not reflected by its physical properties. This is because the cutting action of the LCM very closely simulates the cutting action seen in the field.

Linear Cutting Test Equipment and Procedures

The LCM features a large stiff reaction frame on which the cutter is mounted. A triaxial load cell, located between the cutter and the frame, monitors forces and a linear variable displacement transducer (LVDT) monitors travel of the rock sample. The rock sample is cast in concrete within a heavy steel box to provide the necessary confinement during testing. A picture and a schematic drawing of the LCM are presented in Figure 2 and Figure 3, respectively.

Figure 2: Linear Cutting Test

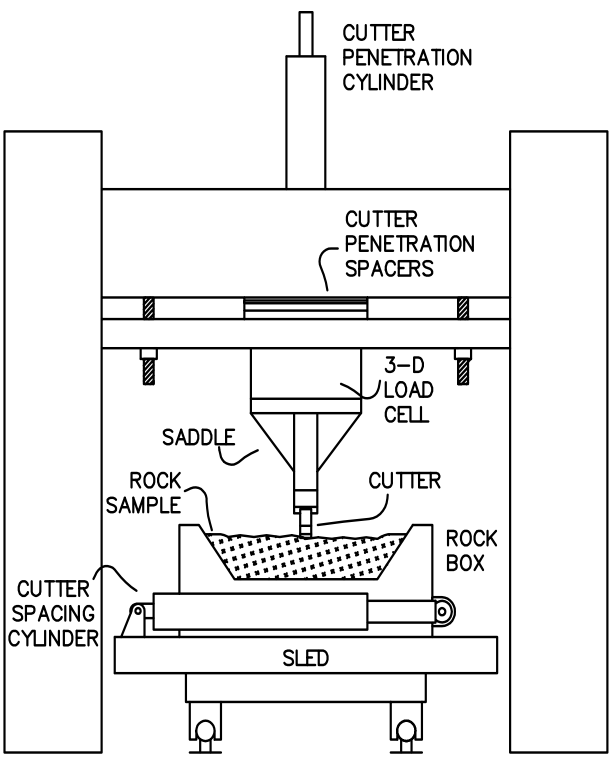

Figure 3: A schematic drawing of the LCM.

A servo controlled hydraulic actuator forces the sample through the cutter at a preset depth of penetration, width of spacing and constant velocity. During the cut, the triaxial load cell measures the normal, drag, and side forces acting on the cutter. After each cut the rock box is moved sideways by a preset spacing to duplicate the action of the multiple cutters on a mechanical excavator. A drawing of the three force components acting on a cutter is shown in Figure 4.

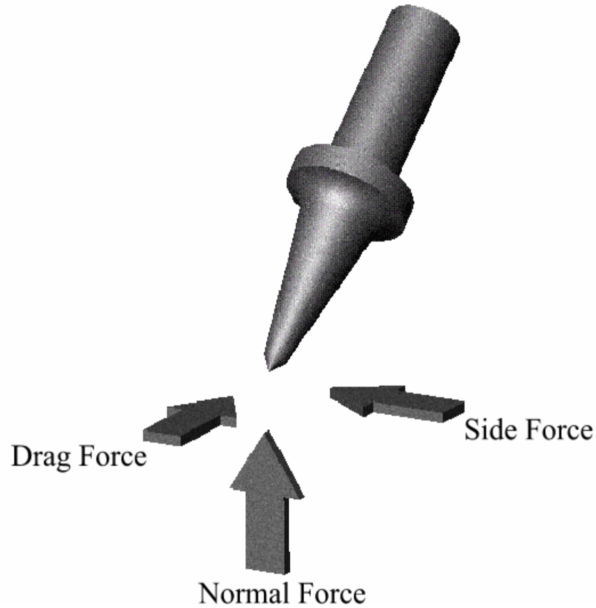

Figure 4: Drawing of forces acting on a pick cutter.

In field excavation, the individual cutters on the machine always operate on a rock surface damaged from the previous cutting action. This scenario is duplicated in the laboratory by thoroughly conditioning the rock surface before testing begins. This is accomplished by making several passes before data is collected. A schematic drawing explaining the nomenclature is presented in Figure 5.

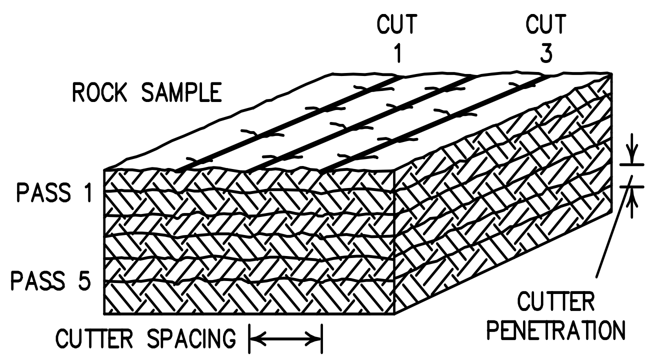

Figure 5: Schematic of a LCM sample and nomenclature.

At the end of each pass of data cuts, muck samples were taken to determine the amount of dust present in the cuttings. To acheive this, 2 carpentry squares were laid over the undisturbed muck to form a sample area. All of the material within the area was collected, using fine brushes to retrieve the fines, and stored in double plastic bags. After the samples were collected, the material was separated for size distribution analysis, using a series of sieve screens. The material passing the finest screen then had their size distribution analysis performed by hydrometer surveys. Figure 6 shows a muck sample to be collected.

Figure 6: Cuttings sample collection.

Linear Cutting Test Parameters

The tests performed for this program consisted of four major variables: cutter type, line spacing between cuts, penetration of cuts, and attack angle. The dependent (measured and calculated) variables were average cutter forces (normal, drag and side), specific energy and muck size distribution for determination of percentages of repirable dust. The constant variables were rock type, cutting sequence (single scroll pattern), cutting speed (10 in./sec., 254 mm/s), skew angle (0°) and tilt angle (0°).

The two different standard point attack bits tested in this program were the U-92 and the U-94 (Figures 7 and 8, respectively), both produced by Kennametal. Both of these bits would commonly be used on continuous miners for producing coal where harder coal measure rocks in the floor or roof are encountered. The U-92 had a 16 mm (0.63") diameter tip and the U-94 had a 19 mm (0.75") tip. Both of the commercially available conical bits had a tip angle of 75 degrees.

Figure 7: U-92, with 16 mm tip.

Three different spacings, 13, 19 and 25 mm (0.5", 0.75" and 1") were tested. The two different tested penetrations were 2.5 and 5.1 mm (0.1" and 0.2"). The tested angles of attack were 47.5 and 52 degrees. Angle of attack is defined as the angle between the bit axis and the tangent of the cut surface (Figure 9). These parameters were chosen to represent the geometries that may be used on a continuous miner designed to operate in a difficult roof rock, such as a hard sandstone.

Figure 8: U-94, with 19 mm tip.

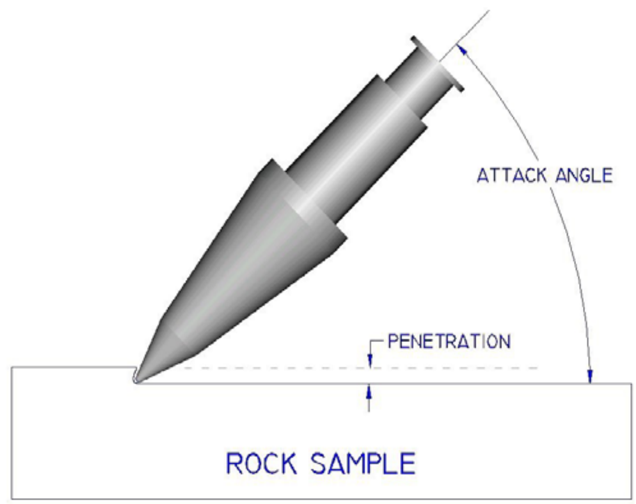

Figure 9: Angle of attack description.

The rock used for the cutting test was Lyons Sandstone. This was a hard abrasive sandstone that is similar to roof rock in many underground coal mines. It is representative of relatively difficult cutting conditions. The Lyons Sandstone had a compressive strength of 120 MPa (17,350 psi) and a tensile strength of 6.1 MPa (890 psi). It should be noted that the Lyons Sandstone is a very abrasive rock, as can be seen by its measured Cerchar Abrasivity Index of 3.3.

Linear Cutting Test Results

The LCM tests have successfully provided data to begin the quantification of the generation of fines based on different cutting geometries. During the cutting tests, forces in all 3 dimensions (normal, drag & side) acting on the bits were recorded to ensure that the cutting action is representative of cutting in the field. The normal force results are a function of thrust required for the cutters to penetrate rock. Cutterhead torque requirements are derived from the drag force results. Cutting coefficient, the ratio of the drag force over the normal force, provides a measure of the direction that the bit is being loaded. And, the specific energy results provide insight to the efficiency of the different cutting geometries. Figure 10 shows a sandstone sample during linear cutting testing. A summary of the force results is presented in Table 1 and descriptions of the tests results follow.

Table 1: Linear cutting force results.

Tool I.D.	Attack Angle	Spacing (mm.)	Pene. (mm.)	Average Forces Normal (kN)	Drag (kN)	Side (kN)	Specific Energy (kWhr/m^3)
U94	48 deg.	12.70	2.54	9.3	5.4	2.8	47.4
U94	48 deg.	19.05	2.54	13.6	7.5	2.5	44.5
U94	52 deg.	12.70	2.54	6.4	3.7	1.3	32.9
U94	52 deg.	19.05	2.54	11.3	6.0	1.0	35.6
U92 KHD	52 deg.	12.70	2.54	4.2	2.9	0.4	25.9
U92 KHD	52 deg.	19.05	2.54	7.1	4.9	1.1	29.0
U92 KHD	52 deg.	25.40	2.54	11.1	7.6	-1.2	33.5
U92 KHD	52 deg.	25.40	5.08	8.9	6.6	-1.3	14.6

Figure 10: Sample during for linear cutting tests.

Normal Force Results

Normal force requirements ranged from 4.2 to 13.7 kN (950 to 3,070 lbf). The wider tip width generated higher normal forces compared to the smaller tip. Wider spacings also generated larger normal forces, while other variables were held constant. The increase in attack angle, from 48 to 52 degrees, created a reduction in the normal forces. This was due to the reduced vertical profile generated by increasing the angle of the bit's axis. And the increase in penetration reduced the normal force, due to more efficient fracture propagation. Chart 1 shows a plot of the normal force results.

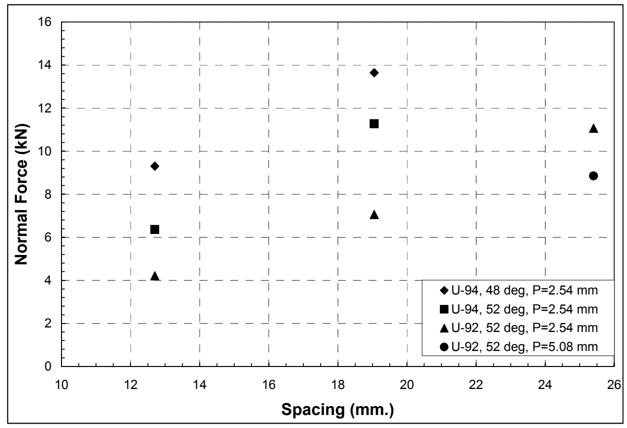

Chart 1: Normal force results.

Drag Force Results

Drag forces ranged from 2.9 to 7.6 kN (660 to 1,700 lbf). As with normal force, the drag forces increased with increases in tip diameter and spacings while the other variables were held constant. The increase in attack angle created an increase in the drag force requirements, which is opposite of the trend for the normal force requirements. And the increase in penetration resulted in a decrease in the drag force, illustrating more efficient fracture propagation. Chart 2 shows a plot of the drag force results.

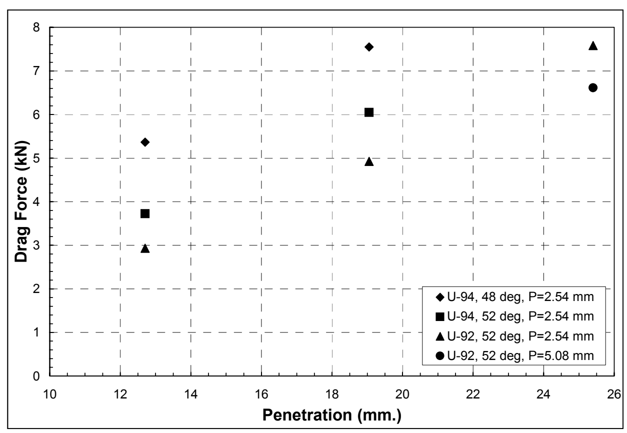

Chart 2: Drag force results.

The ratio of the drag force over the normal force is called the cutting coefficient. The cutting coefficient is the tangent of the result angle and provides a measure of the direction the primary forces are acting on the bit. The difference in resultant angle and the bit axis angle (attack angle) ranged from 16.7 to 23.7 degrees. The smaller tip diameter, at an attack angle of 52 degrees, generated the least differences of 17.0 and 15.2 degrees, for the 2.5 and 5.1 mm (0.1" and 0.2") penetrations, respectively. The wider tip diameter, at the 52 degree attack angle, created the largest difference, averaging 22.6 degrees, between the bit axis and resultant angle. And the wider tip angle combined with the 48 degree attack angle generated a difference averaging 18.4 degrees.

Specific Energy Results

Specific energy is the amount of energy required to excavate a unit volume of rock. It is a function of the drag force and the cross sectional area of the rock being cut. Comparing the specific energy values to the ratio of spacing over penetration helps to identify the most efficient cutting geometry. Chart 3 shows the specific energy results plotted against the spacing / penetration ratio.

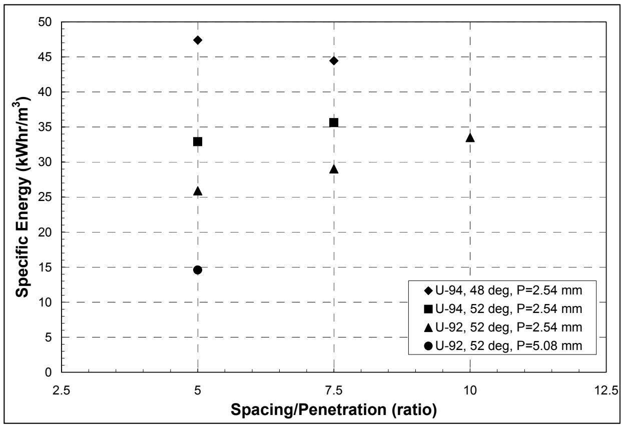

Chart 3: Specific Energy vs. S/P ratio.

The specific energy values ranged from 14.2 to 46.2 kW-hr/m^3 (14.6 to 47.4 hp-hr/yd^3). The 48 degree attack angle, in conjunction with the wider tip diameter, tests produced the highest specific energy values. Increasing the attack angle to 52 degrees resulted in lower specific energy requirements, while holding the other variables constant. Reducing the tip diameter further reduced the specific energy. And the increase in penetration reduced the specific energy by more than half, compared to having all other variables constant.

Sieve Analysis and Dust Determinations

The muck (rock cuttings) samples were collected at each matrix point to define the size distribution. The separation process of these samples involved passing the material through a series of sieves with a roto-tap for 5 minutes. The sieves sizes were 76.2, 38.1, 19.05, 9.525, 4.75, 1.68, 0.841, 0.419, and 0.249 mm (3.0, 1.5, 0.75, 0.375, 0.187, 0.661, 0.0331, 0.0165, and 0.0098 inches). Wet washes were then performed through sieves sizes 0.14986 and 0.07366 mm (0.0059 and 0.0029 inches). The size distribution of the finest material was performed by a hydrometer study. The hydrometer survey provides percentage of material down to the ½ micron level. An example of the detailed size distribution report from an individual matrix point is presented in Figure 11.

Once the size distribution data had been compiled, the mean particle size and percentages of material smaller than 5 and 25 microns were calculated. Percentages of dust ranged from 1.5% to 4.1% and 4.4% to 11.4% for 5 and 25 micron particles, respectively. The data reveals that dust, both 5 and 25 microns, was reduced when lower attack angle, smaller tip diameter, wider cut spacing, and deeper penetration were used. A summary of the percentages of dust is presented in Table 2. Graphic representations of the percentages of 5 and 25 micron particles are presented in Charts 4 and 5, respectively.

Discussion of Linear Cutting Test Results

In order to provide an initial evaluation of the effect of the different variables on the generation of dust, an algebraic comparison was performed on the data produced by the commercially available conical bits. This comparison simply averaged the difference in dust (5 and 25 micron particles) generation for each of the individual tests variables, while the other variables were held constant. The results were then normalized to typical increments of adjustment that would be used on continuous miners operating in a coal mine. The increments of adjustment, used for this analysis, are; attack angle, 1 degree; tip diameter, 2.5 mm (0.1 inch); cut spacing, 6.4 mm (0.25 inch); and cut penetration, 2.5 mm (0.1 inch). These results, shown in Table 3, show that spacing and penetration had a much greater affect on dust generation compared to tip diameter and angle of attack.

COLORADO SCHOOL OF MINES			EARTH MECHANICS INSTITUTE
	SIEVE ANALYSIS		
Project: NIOSH Dust Study	Rock: Lyons Sandstone		Date: 7-21-00
Cutter: U-92 KHD			
Attack Angle: 45 degrees	Spacing: 12.7 mm		Penetration: 2.54 mm

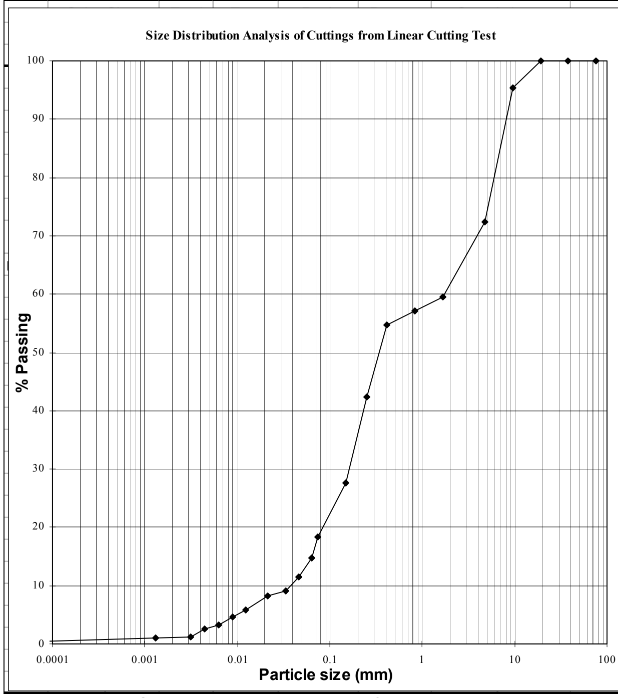

Figure 11: Size distribution result from a cutting test.

Table 2: Percentages of relative dust.

Bit Type	Attack Angle	Spacing (mm.)	Pene. (mm.)	Resperible Dust 5 micron (%)	Resperible Dust 25 micron (%)	Mean Particle Size (mm.)
U-94	47.5	12.70	2.54	2.677	8.494	1.854
U-94	47.5	19.05	2.54	2.355	8.014	2.692
U-94	52	12.70	2.54	4.132	11.359	1.219
U-94	52	19.05	2.54	2.404	6.563	2.946
U-92	52	12.70	2.54	3.684	9.898	1.219
U-92	52	19.05	2.54	2.408	6.280	3.175
U-92	52	25.40	2.54	2.877	7.477	3.124
U-92	52	25.40	5.08	1.484	4.422	3.861

U-92: 16 mm tip dia., 75 deg. tip angle
U-94: 19 mm tip dia., 75 deg. tip angle

In order to provide a more encompassing quantification of the effect of these parameters on dust generation, the statistical method of linear multiple regression was used. Multiple regression analysis was performed to provide equations relating the tip diameter, attack angle, spacing and penetration to the amounts of 5 and 25 micron particles, as well as the mean particle size. The resulting equations produced a high correlation between the test variables and the percentages of dust and the mean particle size. This can be seen by the R-squared values of 74%, 70%, and 86%, for the 5 and 25 micron particles and the mean particle size, respectively.

The resulting slopes from the best fit equations, generated by the multiple regression analysis, provide an evaluation of the effect of the independent variables. These slopes have been normalized to the same increments of adjustment used in the measured evaluation. The magnitude of these slopes, for the 5 and 25 micron particles are presented in Table 4.

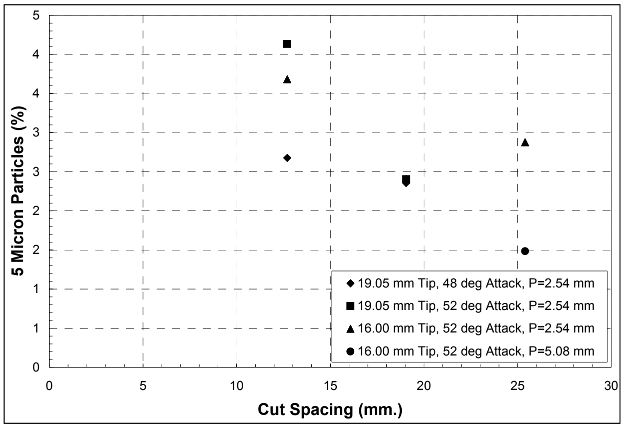

Chart 4: Percentages of 5 micron particles.

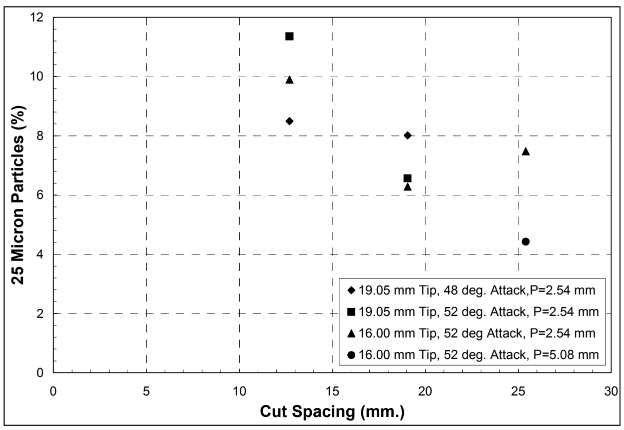

Chart 5: Percentages of 25 micron particles.

Table 3: Average measured effect on dust generation.

Test Variable	5 Micron	25 micron	Units of Evaluation
Attack Angle	0.17	0.16	% dust / degree of attack angle
Tip Diameter	0.18	0.70	% dust / 2.54 mm of tip diameter
Spacing	0.71	1.92	% dust / 6.35 mm of spacing
Penetration	1.39	3.06	% dust / 2.54 mm of penetration

Table 4: Predicted effect on dust generation from multiple regression.

Test Variable	5 Micron	25 micron	Units of Evaluation
Attack Angle	0.17	0.16	% dust / degree of attack angle
Tip Diameter	0.02	0.19	% dust / 2.54 mm of tip diameter
Spacing	0.61	1.69	% dust / 6.35 mm of spacing
Penetration	0.90	1.78	% dust / 2.54 mm of penetration

The trends of the predictor differences followed the same trends of the measured differences. It can be easily seen that spacing and penetration had a much greater effect on dust generation, compared to tip diameter and angle of attack.

DESCRIPTION OF COMPUTER MODEL

The approach used for computer modeling of the cutting drum of a continuous miner is to program each bit individually and analyze the cutting forces acting on the bits. The cutting forces (drag and normal force) depend on the rock type to be cut, the cutting geometry (spacing and penetration of the bits), the geometry of the bit (tip angle) and the attack angle. It is known that the optimum cutting geometry for cutting with drag bit, which results in minimum specific energy requirement and more efficient cutting, occurs at the spacing to penetration ratio of 1-4. This value depends on the rock type and the break out angle, which is the angle of the rock surface created by cutting on both sides of the cut. The ratio of cutting force to normal force on a conical bit depends on the rock type, rock fabric, bit shape, attack angle and depth of penetration. This ratio is typically in the range of 0.5 – 1.0.

Another factor which is important for machine production and dust generation is called spacing, which is defined as the distance between the bits. Larger spacings result in higher efficiency and lower specific energy requirements, given that the material between the bits can be cut. This tends to reduce the dust levels in the working area. However, wider spacings require stronger cutting tools, which usually signifies larger tip diameters and blunter tip angles, which can increase dust generation. Also, the increased spacing and the reduced number of bits on the cutting drum means fewer bits in contact with the cutting area at any given time, causing vibration in the cutterhead. Therefore, the balancing of the drum becomes more important to avoid excessive vibration which is detrimental to the cutting performance and the bit life.

The machine specifications, such as thrust, power and torque, are for providing sufficient amount of forces to the bits, thus supporting the excavation operation. Machine thrust is the force required to penetrate the bits into the rock surface. Also, the cutterhead torque and power requirements are the force to rotate the head at the required penetration rate, and overcome the drag force resistance of the cutters.

To estimate the cutting forces, when full scale linear cutting results are not available, several theories and formulas have been offered. Evans suggested a method for estimation of the cutting forces acting on a conical tool. The formula is as follows:

$$F_c = \frac{16\sigma_t^2 . p^2}{\cos(\alpha)^2 . \sigma_c}$$

Where,

F_c = Cutting force (kN)
p = Depth of penetration per revolution (mm)
α = Half of tip angle (degree)
σ_t = Tensile strength (MPa)
σ_c = Compressive strength (MPa)

In the computer program, a cylindrical coordinate system is used to define the drum geometry and bit-lacing pattern. The position of each cutter on the drum is defined by its radius from the axis rotation, and the position angle from positive x-axis. Figure 12 shows the schematic drawing of a cutterhead and parameters used to define the bit position on the drum. Cutterhead profile data is essential for simulating different cutting modes (sumping and shearing) of the drum and checking the availability of the thrust and power of the machine at a given sumping and shearing depth.

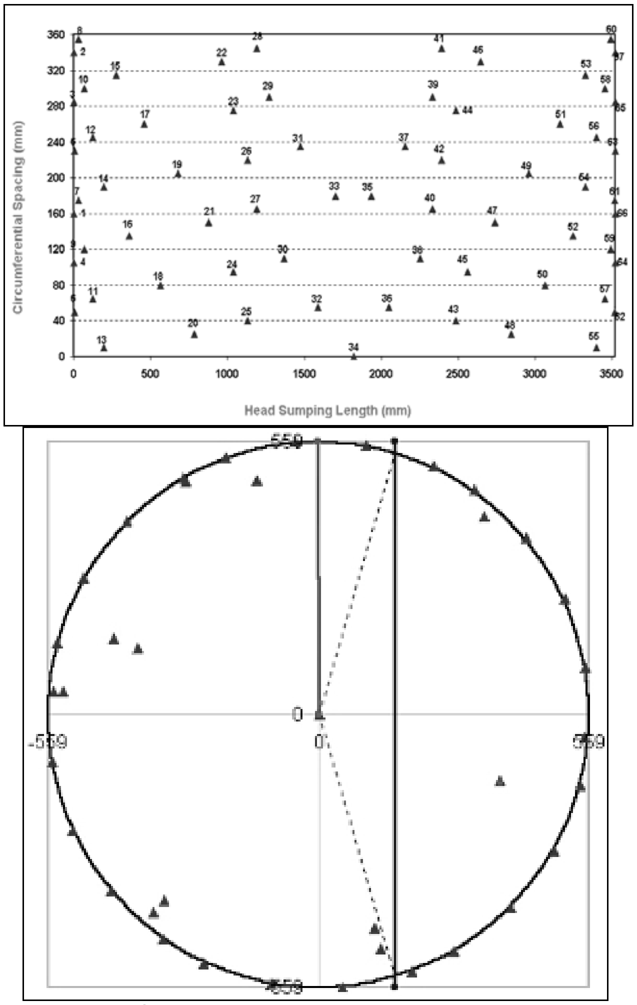

Figure 12: Cutterhead input data

An example of the input window for the cutterhead simulation program for a continuous miner is shown in Figure 13. The information required for the program is project information, machine specification, cutter dimensions, cutterhead position for the cutting mode and rock physical property data.

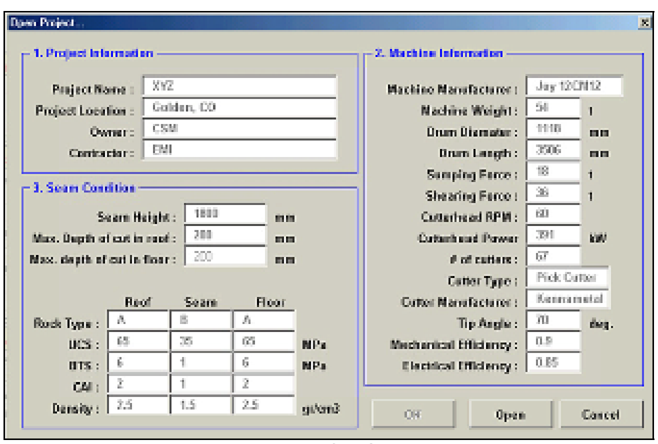

Figure 13: Input data window for CM computer model.

Cutting with a drum creates a continually changing cut penetration profile. If the drum is cutting downward, the cut depth starts infinitely close to zero and approaches its maximum. The model works by rotating the cutterhead 360 degrees and summing the normal and drag forces acting on the individual bits throughout the rotation, with respect to the direction of cutting and axis of drum rotation. Only the cutters engaged in the rock/coal are included in this summation. And the correct forces are used based on each bit's penetration at any given angular location.

The information generated from the computer model includes individual cutter positions, penetration, and forces, overall thrust, torque, and power requirements of the cutterhead in the given position, variation of the forces as the head rotates, and finally, boom speed and production rate. The program allows the user to monitor the variation and graphically represents these variations as the head rotates. Figure 14 illustrates a typical summary of information for a full rotation and variation of thrust, and power for a certain cutterhead design and lacing pattern for sumping and shear-down mode.

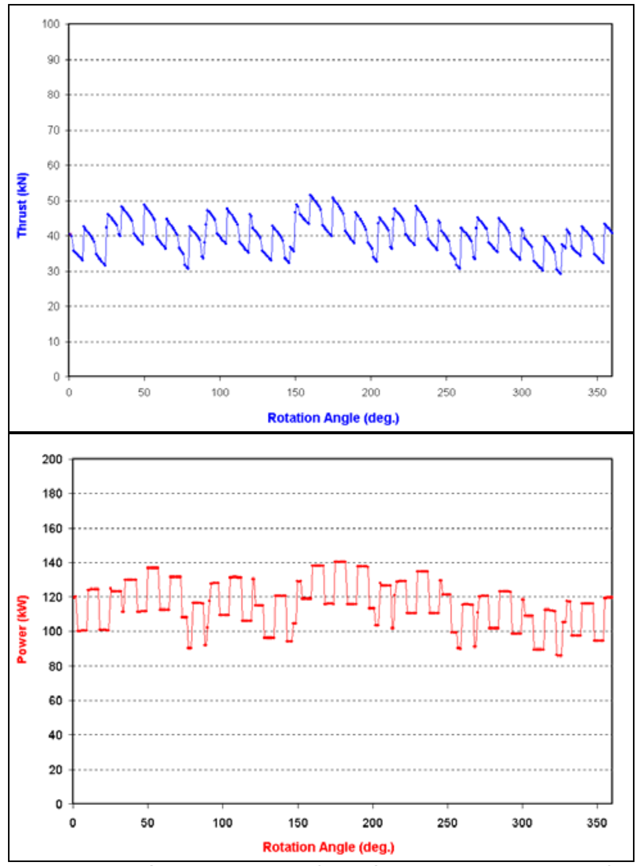

Figure 14: Sample output of the CM modeling program for a full rotation

CONCLUSIONS

Laboratory testing has provided an initial quantification of respirable dust generation related to cutting geometry using state of the art conical bits. While all tested variables had an effect on dust generation, bit spacing proved to be the cutterhead design variable with the greatest effect. Maximizing bit spacing, while ensuring that production concerns are not adversely affected, reduces dust generation. This is true as long as the increase in spacing does not require very different bit design (i.e. diameter and tip angle increasing more than spacing) or prevent the miner from penetrating deeply enough to provide efficient fracturing of the rock/coal. Also, field testing should confirm the trends identified by laboratory testing and provide a more accurate quantification of cutting geometry variables on the generation of respirable dust.

FUTURE WORK

Baseline testing of a continuous miner is scheduled to take place in December 2001. Field testing will consist of several shifts of standard gravimetric sampler respirable dust surveys per MSHA guidelines in conjunction with simultaneous instantaneous production monitoring. Once the baseline field tests have been performed, another round of testing with a new bit lacing pattern will be performed. These field test results will provide an accurate adjustment of the laboratory results and computer modeling efforts for the quantification of the relationship between cutting geometry and respirable dust.

ACKNOWLEDGEMENTS

This work could not have been performed with out the support of NIOSH and the joint efforts of Twenty Mile Coal Company, Joy Mining Machinery and Kennametal. There input has been invaluable and very much appreciated.

This publication was supported by Cooperative Agreement Number U60/CCU816929-02 from the Department of Health and Human Services, Center for Disease Control and Prevention. Its contents are solely the responsibility of the author(s) and do not represent the official views of the Department of Health and Human Services, CDC.

REFERENCES

1. Federal Register, 1999, volume 65, No. 131.
2. Keystone Coal Industrial Manual, 1995, ISBN 0-929531-25-6.
3. Kadui, M., et al, 1991, A New Concept of Clearance Ring Based on the Study of Inclined Pick Behavior, *Proceedings International Symposium on Mine Mechanization and Automation*, Volume 1, pp 1-1 –1-10
4. Nishimatsu, Y., 1972, *International Journal of Rock Mechanics and Mineral Science*, Volume 9, pp. 261-270
5. Evans, I.W., 1984, A Theory of the Cutting Force for Point Attack Picks, *International Journal of Mining Engineering*, Volume 2, Number 1, pp. 63-71.