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Development of a roof bolter drilling control process to reduce the generation of respirable dust

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Abstract The drilling operation in the roof bolting process, especially in hard rock, generates excessive respirable coal and quartz dusts, which could expose the roof bolting operator to continued health risks. Previous research has shown that the amount of respirable dust produced is dependent on the main drilling parameters, specifically the drilling rotational and penetration rate. In this paper, a roof bolter drilling control process was proposed to reduce the generation of respirable dust. Based on the analysis of laboratory drilling test results, a rational drilling control process (adjusting rotational and penetration rates) to achieve the optimal drilling parameter for different rock types was proposed. In this process, the ratio between specific energy and rock uniaxial compressive strength was used as the index to determine the optimal operation point. The recommended drilling operation range for the rock type used in the experiment was provided, and the reduction in respirable dust generation was demonstrated. By following this control process, the drilling efficiency can be monitored in real time, so the system can stay in a relatively high-energy efficiency with less respirable dust production from the drilling source. This algorithm is targeted to be incorporated into the current roof bolter drilling control system for drilling automation so that a safe and productive drilling operation can be conducted in a healthy working environment.

Keywords Roof bolter · Drilling control · Respirable dust · Specific energy

1 Introduction

Roof bolting has been the primary means to improve mine safety in the aspect of preventing different types of roof falls in underground mines in recent decades (Mark 2002). However, based on the published research, underground roof bolting operators exhibit a continued risk for overexposure to airborne levels of respirable coal and crystalline silica dust (size < 10 µm) from the roof drilling operation (Goodman and Organiscak 2002). Inhaling these dusts can cause coal workers' pneumoconiosis (CWP) and another job-related lung disease, silicosis; both illnesses are disabling, even fatal, and irreversible illnesses. Joy et al. (2010) has assessed the dust hazard, especially the respirable quartz hazard, that is present during the roof bolting process by roof bolters with an on-board vacuum dust collection system. Dust sample size distributions and their quartz contents were determined for samples collected from twenty-six mines. The results show that the quartz content in the total roof bolting dust can be as much as 50% with 20% of the samples below 5 µm in size. These quantified results confirm that roof bolting dust can contain high levels of respirable quartz dust. Prolonged exposure to respirable crystalline silica is harmful and can be fatal in instances because these particles reach the gas-exchange region of the lungs and being deposited there increases dramatically the health consequences. A roof bolter operator exposed to a high level of such dust could develop

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silicosis in as little as three years (MSHA 2014). Therefore, the roof bolting function is a major quartz source for causing silicosis in this group of underground miners.

The United States Federal Coal Mine Health and Safety Act of 1969 first included specific procedures for the development of improved mandatory health and safety standards for mining and regulated miners' exposure to coal mine dust by establishing the 2.0 mg/m^3 respirable dust limit. Studies confirmed a beneficial impact of the first 25 years after the Act of 1969 established the prevalence and severity of coal worker's pneumoconiosis (also referred to as black lung disease) among mineworkers in U.S. coal mines (Vallyathan et al. 2011). In 2016, the United States Mine Safety and Health Administration (MSHA) has lowered the concentration limit for respirable coal dust from 2.0 to 1.5 mg/m^3 in the coal mine atmosphere during a working shift and established a quartz dust limit of 0.1 mg/m^3 (Federal Register 2014).

Currently, a dry vacuum dust collection system and canopy air curtain (Fletcher 2013; Listak and Beck 2012; Reed et al. 2019) have been developed to address the roof bolter operator dust exposure issue. But there is still a good amount of dust that could expose the operator to dust hazards, and with these engineering controls and federal regulations in place, new cases of black lung and silicosis continue to be reported and seen in young miners.

Based on the findings from previous research, the amount of generated respirable dust is not only rock formation specific but also drilling parameter specific (Li et al. 2016; Jiang et al. 2018a, b). In this paper, the generated respirable and inhalable (size < 100 µm) dust amount for concrete drilling tests were analyzed, and the process to determine the optimal drilling bite depth range for the purpose of respirable dust control was demonstrated.

2 Laboratory drilling experiments

In order to investigate the relationship between respirable dust generation with drilling parameters, especially drilling penetration and rotational rate, 22 laboratory drilling tests were conducted on a drilling test platform, shown in Fig. 1. This platform was equipped with a drilling control system, a data acquisition system, and a dust collection system. The drilling control system consists of a drill control unit and a drill head. This system attains a pre-set penetration and rotational rate for each drilling test, which then automatically operates the drilling process to try to reach and maintain the pre-set parameters. The data acquisition system, which consists of a set of sensors, attains the drill bit position, drilling penetration and rotational rate, drilling torque (T) and thrust (W). The dust collection system includes a pre-cleaner cyclone and a dust collection box, which enables the collection of dust samples after each drilling test.

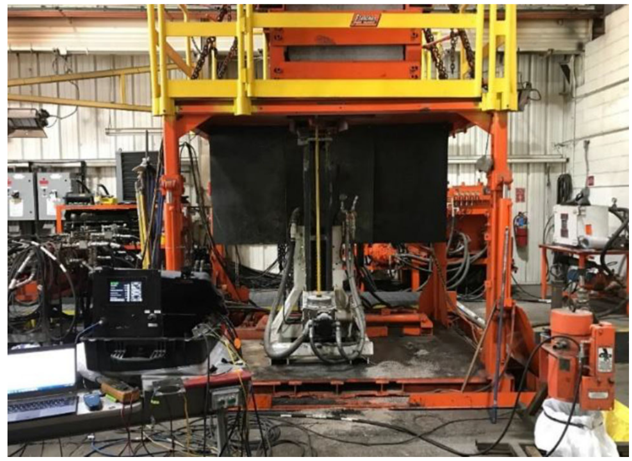

Fig. 1 Fletcher® drilling test platform

For this test, a concrete block with a dimension of 0.91 m $\times$ 0.91 m $\times$ 1.52 m was used as the drilling material. The uniaxial compressive strength of this concrete block is 55.16 MPa, which could represent a medium strength roof rock encountered in underground coal mines. A widely used type of roof bit with a diameter of 3.493 cm, manufactured by Kennametal®, was used for the test as shown in Fig. 2. For each drill test, the bit was replaced with a new bit before drilling each hole.

The tests were designed to cover a full range of bite depth based on the bit design, drilling safety, and available drilling power. In this study, drilling bite depth (b), defined as bit penetration depth per revolution, was introduced to describe the roof bolter drilling process. Drilling bite depth can be calculated from penetration (v) and rotational rate (w), expressed by Eq. (1) below. Twenty-two holes with pre-set bite depth ranging from 0.122 to 0.762 cm/rev were designed to investigate the drilling bite depth impact on dust and energy characteristics. Prior to drilling each hole, the dust collection system was cleaned. After each drilling test, dust samples from the dust collection system were collected and their weights were measured and recorded. A representative quantity of dust from each bulk sample was selected by the coning and quartering method (Zhu 2014),

Fig. 2 Tungsten carbide spade bits used for this test

so that the size distribution for the entire sample could be accurately evaluated. The main drilling test parameters and dust generation results are listed in Table 1. It should be noted that the final achieved drilling bite depth can be different from the pre-set value, which could be caused by poor bit condition or available drilling power.

$$b = \frac{60v}{w}\,(\text{cm/rev}) \tag{1}$$

The specific energy parameter was introduced for energy efficiency evaluation for this study. This parameter is widely used in the drilling literature for the evaluation of the drilling condition and bit selection (Rabia et al. 1986; Farrelly and Rabia 1987). The drilling specific energy is the amount of energy consumed to break a unit volume of rock, expressed in the amount of input energy divided by the rock volume drilled (Teale 1964). Therefore, according to its definition, specific energy can be used as a drilling energy efficiency indicator, as higher specific energy means more energy was consumed during drilling of a unit volume of rock, indicating a lower energy efficiency. The specific energy for rotary drilling can be expressed mathematically in terms of drilling bite depth, penetration rate, torque, and thrust, as shown in Eq. (2) (Luo et al. 2004).

$$\varepsilon = \frac{2\pi T}{A_b b} + \frac{W}{A_b} \tag{2}$$

where, A_b is the borehole area, cm^2; b is the drilling bite depth, cm/rev; and T and W are the torque and thrust in N m and N, respectively. It should be noted that all these parameters were monitored and recorded in real time by the drilling control system.

3 Rational drilling parameter determination

Figure 3 plots the bite depth versus the main results from these tests, drilling specific energy, noise dose, and inhalable and respirable dust weight. The noise dose data used in Fig. 3 are from a previous research project (Li 2015). As the plot demonstrates in Fig. 3, for the drilling tests with larger bite depth, the drilling specific energy reduced significantly, indicating that a better drilling efficiency was achieved. The drilling specific energy was decreased by

Table 1 Drilling parameters and feedback results for each drill hole

Test No.	Achieved			Thrust (N)	Torque (N cm)	Total sample weight (g)	Total inhalable dust weight (g)	Total respirable dust weight (g)	Specific energy (N/cm^2)
	v (cm/s)	w (rev/min)	Bite depth (cm/rev)						
1	1.15	462	0.150	4133.1	8608.4	3423.5	2268.6	839.6	29,255.7
2	1.09	392	0.167	4363.4	9466.5	3342.6	2023.2	710.3	28,821.4
3	1.61	470	0.205	4352.3	8657.8	3396.1	2068.3	753.0	21,586.2
4	1.78	502	0.213	5064.1	8865.5	3208.5	1902.2	677.4	21,359.5
5	1.58	409	0.232	4790.0	9694.5	3345.2	1970.6	703.7	21,421.6
6	2.06	503	0.246	4794.6	8777.3	3147.1	1820.4	619.0	18,322.1
7	2.11	491	0.257	4946.0	9237.2	3467.0	1984.7	709.0	18,444.3
8	2.32	501	0.277	5884.0	9468.8	3212.5	1917.6	768.1	17,650.8
9	2.04	425	0.288	4990.2	9683.6	3488.2	1927.2	672.6	17,320.7
10	2.51	515	0.292	5345.5	9704.2	3438.7	1930.2	696.5	17,130.5
11	2.70	510	0.318	5357.6	9734.4	3405.8	1859.7	665.7	15,833.9
12	3.33	503	0.398	6338.9	10,147.4	3465.7	1857.5	681.9	13,344.2
13	2.91	453	0.386	5949.7	8655.8	3382.3	1648.5	648.1	11,764.7
14	3.06	441	0.416	6412.8	10,256.6	3458.7	1651.8	558.0	12,918.5
15	3.67	504	0.437	6508.5	10,114.4	3420.4	1830.1	666.9	12,175.9
16	3.53	499	0.425	6893.2	10,156.4	3061.3	1742.7	672.8	12,582.1
17	4.24	458	0.556	7065.8	11,595.7	3296.8	1775.7	649.8	11,064.6
18	3.73	398	0.562	7452.8	10,290.0	3340.7	1719.8	616.3	9803.5
19	5.07	505	0.602	8532.6	11,347.3	3309.1	1757.6	645.3	10,162.1
20	4.25	399	0.640	8429.6	10,641.2	3358.1	1724.2	644.7	9045.8
21	5.46	427	0.767	10,992.0	11,474.0	3437.1	1730.9	653.2	8401.2
22	5.06	397	0.765	9722.8	11,478.7	3356.0	1785.7	656.7	8323.2

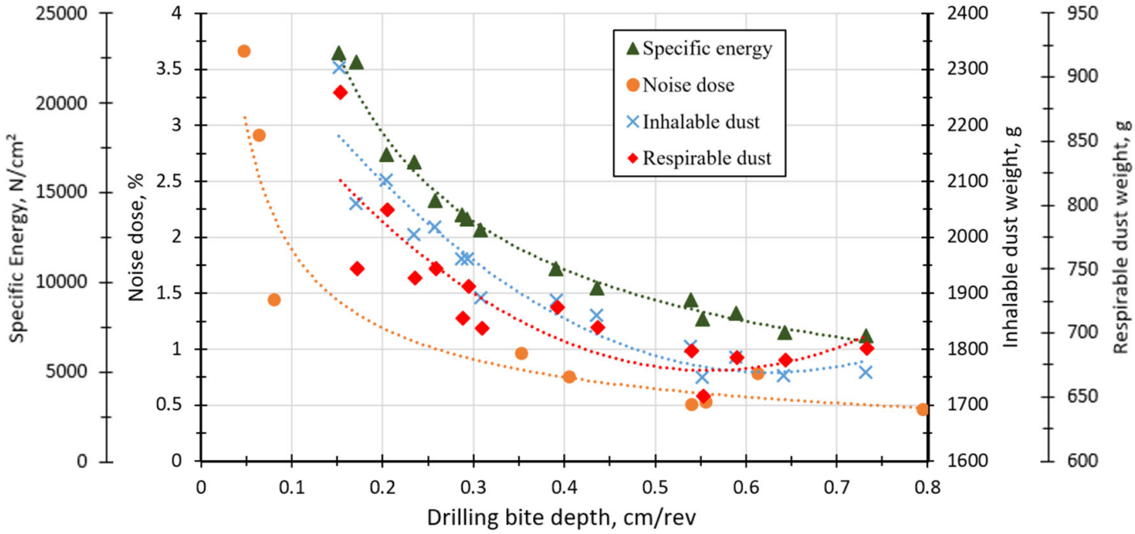

Fig. 3 Relationship of drilling bite depth with noise dose, dust weight, and specific energy

70% by increasing the bite depth from 0.152 to 0.732 cm/rev. The noise dose rapidly decreases as the bite depth increases until it reaches its minimum value at a bite depth that equals 0.541 cm/rev. Afterwards, the noise dose value keeps almost constant. For the dust weight results, the plot shows the same trend as noise versus bite depth, with both the inhalable and respirable dust amount reduced while increasing the drilling bite depth before the bite depth reaches 0.551 cm/rev. Then, the amount for inhalable dust becomes stable while an increasing trend is shown for the respirable dust. The inhalable dust weight has reduced by 550 g from the highest to lowest drilling bite depth. Meanwhile, the respirable dust weight has decreased by 200 g.

From the discussed test results, it can be deduced that drilling with a high bite depth is beneficial to dust control, noise reduction, and energy efficiency. But since the noise and dust curve leveled out at around 0.55 cm/rev bite depth and the decreasing rate of specific energy slowed down after this point, so this operating point can help to determine the recommend operating range. Therefore, the bite depth range from 0.50 to 0.60 cm/rev was recommended based on this specific rock and type of bit for the purpose of dust reduction while still maintaining a good drilling efficiency.

4 Development of the drilling control process

Based on the results from the drilling energy and dust generation analysis, the rational drilling bite depth should be in the range from 0.50 to 0.60 cm/rev for the tested concrete.

However, the optimum bite depth range is correlated with the rock material that has been drilled, and this range could be quite different from one mine site to another. Due to this reason, the ratio (δ) between specific energy and uniaxial compressive strength (UCS) was used as an indicator to identify the optimal drilling bite depth for different rock materials. Specific energy is not only drilling parameter specific, but also formation specific. Real-time optimization of drilling parameters for bolt hole drilling can be performed by identifying the optimal bite depth in the specific formation based on specific energy surveillance. A similar approach was used and proved to be effective in the optimization of the drilling parameters for rotary downhole drilling (Chen et al. 2016). Therefore, the ratio (δ) could provide an objective tool to determine whether the drilling was conducted in its optimum performance range.

The relationship between drilling bite depth and the ratio of specific energy over UCS from concrete drilling

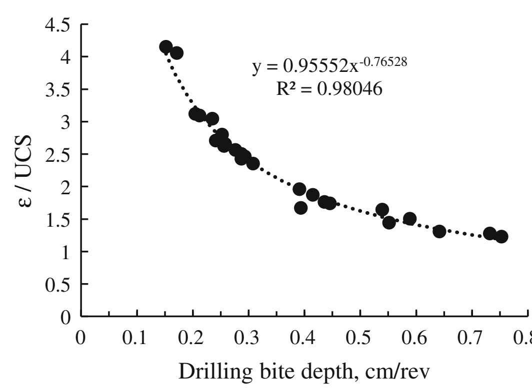

Fig. 4 Relationship between drilling bite depth with the ratio of specific energy over UCS

tests can be plotted as shown in Fig. 4. Their relationship fits a power function with negative power. As the bite depth increases, δ becomes smaller, which indicates a better efficiency. But according to the dust and noise generation analysis, the recommended bite depth range is from 0.5 to 0.6 cm/rev. Therefore, the optimum δ range is determined from 1.35 to 1.60, and this optimum range is supposed to be applicable to all material types, but more surveillance data needs to be analyzed on different drilling materials to confirm this theory.

With the optimal δ range determined for this type of rock, the process of adjusting drilling parameters to reach the drilling optimal bite depth is shown in Fig. 5. Since a higher rotational rate would accelerate bit wear, a lower rotational rate combination with a correlated penetration rate to reach a designated drilling bite depth is preferable.

In this drilling control process, an initial bite depth and the rock UCS need to be assigned into the drilling control system before the start of drilling. As the drilling progresses, the specific energy is monitored, and δ can be calculated simultaneously. If the δ value falls into the range from 1.35 to 1.60, then the system will continue drilling with the initial bite depth. However, if the δ value is higher than 1.60, then the system will first try to reduce the rotational rate to lift the bite depth in order to reduce the specific energy to meet the criteria until the torque has reached its cap value. Then, the system will increase the penetration rate by raising the thrust power. However, when thrust is increased to its cap value and δ is still beyond 1.60, the most likely reason is that the effective thrust is too low, which is caused by excessive bit wear. Therefore, it will trigger a stop and check alert, which would require the operator to address the issue. If the δ value is lower than 1.35 at the beginning, the system will lower its thrust power to decrease the penetration rate in order to increase the specific energy.

By following this drilling control adjusting process, the system can maintain drilling within the optimum bite depth range, so that the drilling can be operated in a relatively high energy efficiency range with less respirable dust

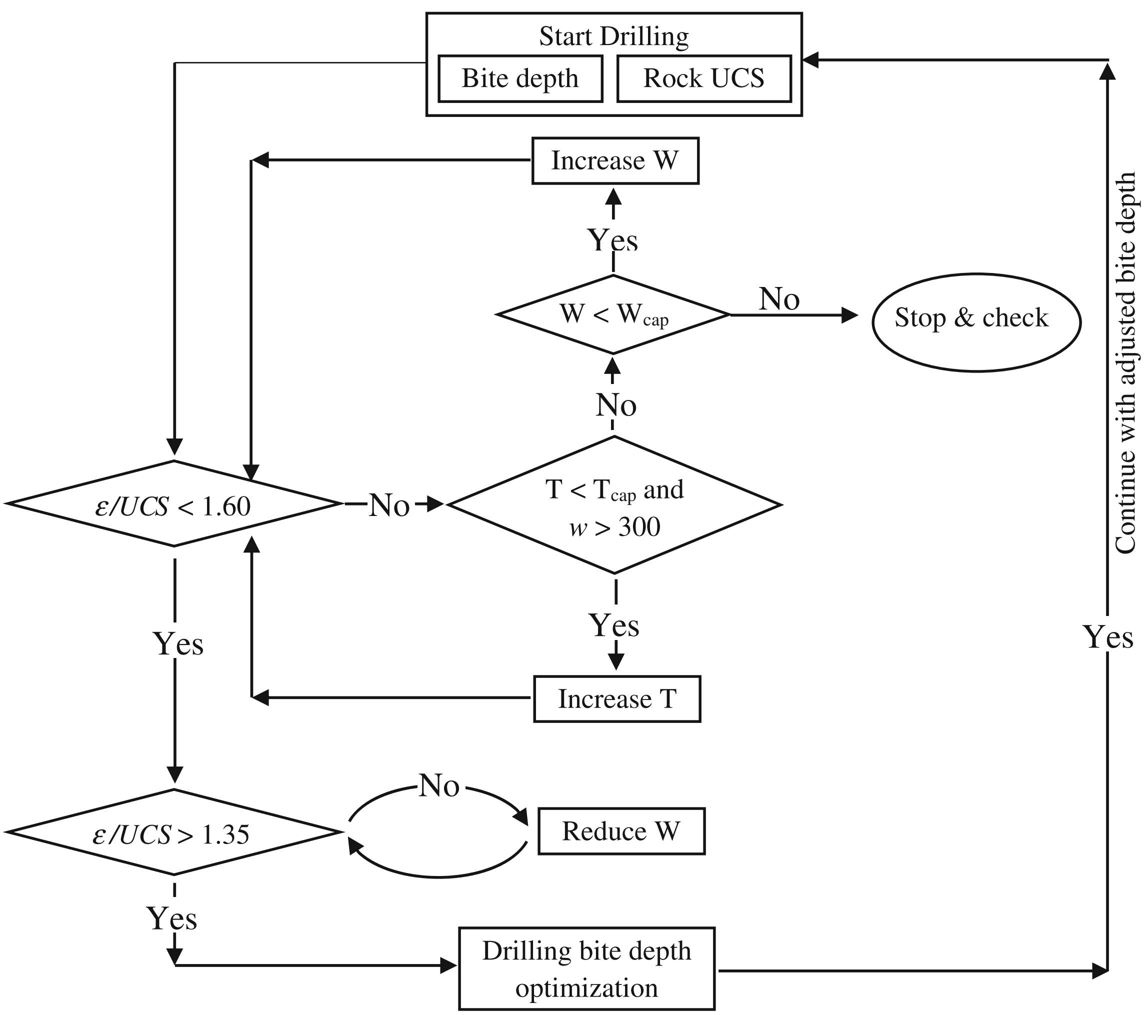

Fig. 5 Schematic diagram of the drilling control algorithm

production. Due to the limitation of the data source, to improve the feasibility of this process, more dust and energy input results from drilling different types of rock need to be collected for the calibration process.

5 Conclusions

In this study, 22 laboratory drilling tests were conducted. The particles generated from each drilling were analyzed, and their weights and size distributions were obtained. In addition, the energy input was analyzed for the efficiency evaluation. On average, from one drilling hole, 20.2% of the total generated particles can be respirable and 55.5% can be inhalable size range. By analyzing the effect of drilling bite depth on energy and dust generation rate, an exponentially decreasing trend was observed between drilling specific energy and bite depth. Therefore, it is advantageous to have a high bite depth to achieve better energy efficiency. The dust generation characteristics showed a considerable reduction in both inhalable and respirable dust generation rate when increasing bite depth from 0.15 to 0.60 cm/rev. However, no further reduction in dust generation rate was observed under greater bite depth.

Finally, based on the test results and analysis, a rational drilling control process was proposed to optimize the drilling efficiency, while reducing the respirable dust generation. Because the optimum bite depth range is correlated to the ratio between specific energy and the UCS, an optimum ratio range of 1.35–1.60 is recommended based on the concrete drilling result. This proposed process can help to keep the drilling operation with an optimum efficiency while maintaining the dust generation rate at a lower level.

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