Technical Note

Effect of skew angle on main precursor of frictional ignition in bench-scale simulation of excavation processes

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1. Introduction

Frictional ignition in coal mining usually occurs when the cutting bits of a mining machine drill rocks. This is one mechanism that has been speculated to underlie the phenomena of ignition and explosion. The heat generated in the process of cutting geomaterials can potentially ignite methane clouds and lead to explosions; hence, friction mitigation in the mining industry is crucial for improving mining safety. In recent years, the Massey Mine explosion in West Virginia in 2010, which killed 29 people, has served as an unforgettable reminder that friction ignition can cause disastrous mine accidents when it is poorly controlled. This incident is believed to have been triggered by a spark on the cutting face, which ignited methane clouds and propagated quickly to coal dust. Because water is widely used to suppress friction ignition, this accident suggests that water cannot be a completely reliable countermeasure to prevent mine explosions. Therefore, it is essential to advance new techniques that mitigate the occurrence of friction ignition during mine excavation. To prevent mine explosions and thereby improve mine safety, the mechanisms that underlie friction ignition should be thoroughly understood.

According to friction ignition statistics for Australian and South African coal mines between 1990 and 2010, one to five incidents have been reported nearly every year, with several lives lost in each accident. Some researchers found that 90% of all friction ignition incidents occurring in underground coal mines liberated at least 0.39% of methane gas (CH₄) through their ventilation systems, and claimed there was no significant relationship between gas content and number of friction ignition incidents. In contrast, other researchers reported that friction ignition occurred in coal and gold mines, which could liberate even less methane (between 0.02% and 0.05%) through their ventilation air methane systems. There are several ignition sources such as chemical reactions, electrical heat energy, mechanical heat energy, and nuclear decomposition. Among them, frictional ignition is one of common mechanical heat energy sources. Some researchers have discussed frictional ignition in terms of hot spots, which were proposed as a potential explosion source caused by frictional abrasion and complex cutting-abrasion phenomena. However, few studies have analyzed contact phenomena such as the formation of hot spots; hence, little understanding of the contact mechanism has been achieved. To minimize spark generation, many engineers have suggested selecting proper shank materials and cutting bit materials. For example, a mushroom shape for bit inserts, 4340 steel for the shank, and tungsten carbide for the cutting bit tip have been widely used in mine excavation.

To prevent frictional ignition in mines, its precursors must be thoroughly characterized and evaluated. In discovering the primary cause of frictional ignition, it is important to understanding how the temperature of a cutting tool changes depending on the skew angle between the cutting tool and excavated material.
Some researchers suggested that the contact area of tool-chip is an important parameter in controlling heat transfer into the cutting tool. Thus, a small contact length suggests that a low percentage of the generated heat flows into the tool. Also, temperature distribution and heat partitioning in cutting tools are important factors when designing cutting tools as temperature and heat can influence the performance and lifetime of cutting tools as well as quality of the machined product. However, these are beyond the scope of this paper. One interested pursuing this scope could start by reading other papers.

For this study, a bench-scale device, which facilitates mechanical contact between a cutting tool and a rock wheel, was used to examine the correlation between the skew angle of a cutting bit and the temperature increment of its tip. The skew angle is an important parameter in excavation processes because an optimum angle is required to increase the lifetime of a cutting bit. However, the effect of the skew angle on the temperature increment—the main precursor of frictional ignition—has not been systematically tested.

In this paper, possible remedies are proposed for reducing or minimizing sparking occurrences by understanding the effect of skew angle on the temperature increment of bit tips as a function of the bit-tip shape. The results provide insight into designing cutting bits with safer shapes, and may contribute greatly to improving safety in the mining industry.

2. Design and fabrication of testing machine

This study began with the design and fabrication of the frictional ignition-testing machine (Fig. 1). The rock wheel on the machine (10 in. in diameter, 11/8 in. in thickness) was fabricated from a granite countertop, using a water jet machine. The wheel was mounted on a shaft (1 in. in diameter, 18 in. in length) equipped with heavy-duty ball bearings. It was turned by a motor (1/2 hp torque) connected to the shaft with a sheave and belt arrangement. The speed was controlled by adjusting the sheave size and belt.

The test device was designed by considering the three important angles shown in Fig. 2. The clearance angle ("A" in Fig. 2) is the angle between the physical edge of the bit and the plane struck by the bit. Each of the four bit types tested had a unique clearance angle (Fig. 3). The contact angle ("B" in Fig. 2) is the angle between an imaginary line running through the center of the bit and the plane struck by the bit. As reported by some publications, attack angles of 45° to 50° and a mushroom-shaped cutting bit reduce spark ignition in mines. Therefore, a 45° attack angle and tungsten carbide tips were used, both of which are widely used in mine excavation. The skew angle ("C" in Fig. 2) is the angle between an imaginary plane perpendicular to the direction of cutting and the imaginary line running through the center of the bit. For the test device, the axis of rotation was the shaft on which the rock wheel was mounted. For a continuous miner or longwall shearer, the axis of rotation was the centerline of the cutting drum. For each test, a cutting tool or bit was mounted in the bit housing on the lever arm (Fig. 1A). The housing can be rotated to adjust the skew angle of the bit. Testing was performed at skew angles of 0°, 3°, 6°, 9°, 12°, and 15°. Tip angle, surface area, and weight of cutting tools used in the experiment were measured (Table 1). Tip angles and dimensions were measured from photographic images of the tools by using ImageJ software to calculate the surface area.

3. Procedure for cutting tests

The granite rock wheel was mounted on the testing machine, and the cutting tool was positioned on the granite wheel (near the top) at a specific skew angle. The blasting chamber was lowered to isolate the testing machine. As the chamber of the testing machine was exposed to air, ventilation was not used in this study. Testing experiments were run at room temperature (18–22 °C) for 7.2 s in the short duration test and 200 s in the long duration test while 900- and 30-Hz recordings were made with two different infrared (IR)
4. Data collection and analysis

Short and long duration tests were performed for four bits at varying skew angles (0°–15° in 3° steps). For the short duration test, the rock wheel rotated at 500 rpm for 7.2 s or for 60 revolutions without any additional weight on the bit. The temperature of the bit tip was recorded with a 900-Hz high-speed IR camera. For the long duration test, the rock wheel rotated at 1000 rpm for 200 s with an additional 2.27-kg weight on the bit. The temperature of the bit tip was recorded with a 30-Hz IR camera and a thermocouple. Data were analyzed with programs specific to the IR camera used (Fig. 4). For the high-speed IR camera, the emissivity factor was 0.85 for the tungsten tip. For the low-speed IR camera, the thermocouple method was used instead of emissivity factors to calibrate the data.

5. Results and discussion

The temperature change (ΔT), defined as the difference in the temperature of the bit tip before and after a cutting test, was plotted to depict the effect of skew angle on bit tip heating. ΔT was expected to increase with the skew angle because increasing the skew angle can increase the contact area between the bit tip and rock wheel and hence the friction energy. However, the results for the short duration tests mostly showed no effect of skew angle on ΔT for all four bits (Fig. 5) with high speed IR camera. Although ΔT in S1 was significantly higher at a 12° skew angle than at a 0° skew angle, there was no correlation between skew angle and ΔT (Fig. 5B and Table 2), test whether a longer cutting time would reveal an effect, the cutting time was extended to 200 s.

For the long duration test, a non-zero skew angle significantly increased ΔT for both B1 and B2 (Fig. 6A). Compared with the control condition (zero skew angle), ΔT increased by ~10.5–34.1% and ~37.2–56.5% across all non-zero skew angles for B1 and B2, respectively (Table 3). These results indicate that the skew angle effect on ΔT was greater for B2 than for B1. This difference in effect between B2 and B1 may be due to the different surface areas of the bit tips (Table 1).

In contrast to the case for B1 and B2, the effect of skew angle on ΔT was relatively weak for S1 and S2 (Fig. 6B). Given that the surface areas of B2 and B1 are much larger than those of S1 and S2 (Table 1), these results suggest that the surface area of the cutting bit tip is positively correlated with the extent to which the skew angle increases ΔT during excavating processes. In particular, non-zero skew angles had no effect on ΔT for S1 when compared with the control condition (at zero skew angle), whereas the effect was significant at 12° and 15° for S2. In addition, ΔT increased by ~26.8% at 15° for S1 and by ~43.2% at 15° for S2 relative to their respective control conditions (Table 3). Both the surface area and skew angle effect of S2 are larger than those of S1. Consistent with the results obtained from B1 and B2, these results support the conclusion that the larger the surface area of the cutting bit tip, the greater the effect of skew angle in increasing ΔT.

The surface contact area between a cutting tool and a rock wheel is an important determinant of the impact of skew angle on ΔT. The effect of skew angle on ΔT in B2 (the largest surface area) and B1 (the second largest surface area) bit was revealed around 40–80 s cutting time even at small skew angles, 6° and 9° (Fig. 7A and B). In contrast, in smaller surface area tips (S2 and S1), the skew angle effect on ΔT increase was not significant at the small skew angles for the overall 200 sec cutting period (Fig. 7C and D). These results support the conclusion that the skew angle effects on ΔT increase are greater in the large surface area tips. Nonetheless, further research is necessary to determine the relationship between bit tip angle and the impact of skew angle on ΔT because

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**Table 1**

<table>
<thead>
<tr>
<th>Cutting tools</th>
<th>Tip angle (deg)</th>
<th>Surface area (cm²)</th>
<th>Weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2</td>
<td>79.9</td>
<td>4.3</td>
<td>1133.2</td>
</tr>
<tr>
<td>B1</td>
<td>79.5</td>
<td>3.2</td>
<td>836.9</td>
</tr>
<tr>
<td>S2</td>
<td>69.3</td>
<td>2.5</td>
<td>677.5</td>
</tr>
<tr>
<td>S1</td>
<td>60.6</td>
<td>1.2</td>
<td>558.8</td>
</tr>
</tbody>
</table>

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Fig. 4. Snapshot images obtained with IR data processing programs for the high-speed (A) Data Cube Viewer and low-speed (B) Research IR program.
the bit tip angle can also markedly affect the surface contact area between the bit tip and rock wheel. For example, the tip angles of B2 and B1 are very similar to one another, whereas the angle of S2 is wider than that of S1. Therefore, any tip angle effect on ΔT can be increased along the skew angles when compared to no skew angle (short time duration, 7.2 s).

Importantly, the bit weight and ΔT appear to be negatively correlated at a skew angle of zero. B2 is heavier than B1 (Table 1) whereas the difference of ΔT between B1 and B2 was only ~3.2% higher at zero skew angle than that for B2; however, the difference of ΔT between B1 and B2 was statistically insignificantly at skew angles of 3°, 6° and 12°; on the contrary, no difference in ΔT between S1 and S2 was not observed at non-zero skew angles (Fig. 8). These data also suggest that ΔT is greater in a lighter bit (S1) than a heavier bit (S2) at zero skew angle, whereas the effect of skew angle is greater when the tip surface area of a bit is larger.

In addition, the tip surface area and ΔT seem to be negatively correlated at the zero skew angle as the elevated ΔT in large tip surface area was lesser than in the small tip surface area, 19.8% for non-zero skew angles, suggesting that a bit with a large tip surface area (B2) is more likely to show an increase in ΔT as the skew angle is increased than is a bit with a small tip area (B1). Trends similar to those for B1 and B2 were also observed for S1 and S2. S2 is heavier than S1, whereas the angle of S2 is wider than that of S1. Therefore, any tip angle effect on ΔT can be enhanced along the skew angles when compared to no skew angle (long time duration, 200 s).

![](image1)

**Fig. 5.** Temperature change of bit tip (ΔT) as a function of skew angle in the short duration (7.2 s) test. ΔT for bit tips B1 and B2 (A) as well as S1 and S2 (B) were analyzed with the Data Cube Viewer data processing program. *Statistically different from zero (0) skew angle at P < 0.05 by Student’s two-tailed t-test. Error bars show standard error of the mean (SEM, 2 ≤ n ≤ 3).**

### Table 2

<table>
<thead>
<tr>
<th>Cutting tools/Skew angles</th>
<th>3° (%)</th>
<th>6° (%)</th>
<th>9° (%)</th>
<th>12° (%)</th>
<th>15° (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2</td>
<td>–37.6</td>
<td>11.1</td>
<td>–9.3</td>
<td>39.6</td>
<td>11.1</td>
</tr>
<tr>
<td>B1</td>
<td>2.2</td>
<td>–2.3</td>
<td>–18.3</td>
<td>9.8</td>
<td>11.6</td>
</tr>
<tr>
<td>S2</td>
<td>27.8</td>
<td>4.8</td>
<td>–3.4</td>
<td>10.8</td>
<td>4.4</td>
</tr>
<tr>
<td>S1</td>
<td>31.2</td>
<td>31.5</td>
<td>32.4</td>
<td>113.8</td>
<td>31.9</td>
</tr>
</tbody>
</table>

* Statistically different from zero (0) skew angle at P < 0.05 by Student’s two-tailed t-test (n = 2 or 3).

### Table 3

<table>
<thead>
<tr>
<th>Cutting tools/Skew angles</th>
<th>3° (%)</th>
<th>6° (%)</th>
<th>9° (%)</th>
<th>12° (%)</th>
<th>15° (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2</td>
<td>37.2*</td>
<td>42.7*</td>
<td>51.6*</td>
<td>56.5*</td>
<td>49.0*</td>
</tr>
<tr>
<td>B1</td>
<td>10.5</td>
<td>21.2*</td>
<td>28.1*</td>
<td>33.1*</td>
<td>34.1*</td>
</tr>
<tr>
<td>S2</td>
<td>10.8</td>
<td>1.0</td>
<td>18.1</td>
<td>29.0*</td>
<td>43.2*</td>
</tr>
<tr>
<td>S1</td>
<td>–0.4</td>
<td>1.3</td>
<td>17.8</td>
<td>19.2</td>
<td>26.8</td>
</tr>
</tbody>
</table>

* Statistically different from zero (0) skew angle at P < 0.05 by Student’s two-tailed t-test SEM (7 ≤ n ≤ 9).
supporting the evidence that the large tip surface area can dissipate heat faster than the small surface area tips. However, the increasing \( \Delta T \) at non-zero skew angles was greater in the large surface area tips than in the small surface area tips. The rate of heat generation in the large tip surface area can exceed the rate of heat dissipation by skew angle increment whereas S1 (smallest surface area) did not reveal increasing \( \Delta T \) with respect to skew angles. These results suggest that the large surface area tips can dissipate heat faster at zero skew angle, but at non zero skew angle, the rate of heat generation can be much faster than the rate of heat dissipation with the increase of skew angles. Thus, both the bit weight and surface area seem to be critical determinant of \( \Delta T \) at zero skew angle, whereas the tip surface area appears to be a more important determinant of \( \Delta T \) at non-zero skew angles. To further analyze the quantitative effects of bit weight and surface area on \( \Delta T \), a new set of bits having same weight with different tip surface area or vice versa (same surface area with different weight) needs to be tested.

Bits B1 and S1 are used mainly in coal excavation, whereas B2 and S2 are efficient for rock excavation. Interestingly, the maximum \( \Delta T \) (relative to \( \Delta T \) at zero skew angle) at any non-zero skew angle for coal excavating bits (B1 = 34.1% and S1 = 26.8%) was much weaker than that for rock excavating bits (B2 = 56.5% and S2 = 43.2%) (Fig. 9). This suggests that tip shapes with a smaller surface area and narrower tip angle reduce the \( \Delta T \) more effectively by minimizing the surface contact area between the cutting tool and excavating material. These results, therefore, provide insights into how bit tip shapes should be designed; small tip angle and surface area of bit tip can be possible remedy to reduce the temperature increment when skew angles applied.

**Fig. 7.** Temperature measurements (\( \Delta T \)) of the bit tips (B1 (A), B2 (B), S1 (C), and S2 (D)) parameterized by skew angles (0, 3, 6, 9, 12, and 15°). Temperature changes of representative each bit tip were measured and analyzed every 40 s for 200 sec.

**Fig. 8.** Temperature change of bit tip (\( \Delta T \)) as a function of skew angle in the long duration (200 s) test. Comparison of \( \Delta T \) between B1 and B2 (A) as well as S1 and S2 (B) were analyzed with Data Cube Viewer data processing program. *Statistical difference between B1 and B2 (A) as well as S1 and S2 (B) at \( P < 0.05 \) by Student’s two-tailed \( t \)-test. Error bars show SEM (7 \( \leq n \leq 9 \)).
and Sivash Nadimi for their technical assistance.

ments in the mining industry.

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wheel was examined. Although non-zero skew angles are used to

cavation process in the mining industry. With a bench-scale de-

6. Conclusions

In summary, understanding the main precursors of frictional

ignition is crucial for improving workplace safety during the ex-
cavation process in the mining industry. With a bench-scale de-
vice, the friction ignition process between a cutting tool and a rock
wheel was examined. Although non-zero skew angles are used to
increase the lifetime of cutting tools during excavation, the pre-
cursor of friction ignition (i.e., bit tip temperature) increases with
the skew angle of a cutting tool. The main findings of this study are
as follows: (1) tests conducted for a longer duration exhibited
greater effects on the temperature increment at the bit tip (\(\Delta T\)) for
non-zero skew angles; (2) the skew angle significantly affected the
\(\Delta T\), with stronger effects for bits B2 and S2, which had larger tip
surface areas than did B1 and S1; (3) lighter bits (B1 and S1) ex-
hibited a higher \(\Delta T\) than did heavier bits (B2 and S2) especially for
zero skew angle; and (4) the \(\Delta T\) increment at non-zero skew angles
was more drastic in larger surface area tips (B2 and B1) than
small surface area tips (S2 and S1). The results of this study will be
useful for cutting bit technology, and should particularly be infor-
mative for drum designers, miners, and federal government
officers, who are interested in improving safety in work environ-
ments in the mining industry.

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