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An experimental study on wearing of conical picks interacting with rock
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Abstract

Wearing of conical picks on a coal mining machine and roadheaders are investigated experimentally using a full-scale rotary cutting machine. This study considers three types of conical picks with different tip materials to examine the effects of the wear resistance of conical picks and the wear characteristics in response to cutting load. The influence of pick wear on the cutting load and the pick tip temperature is analyzed, thereby providing an experimental-based guideline for reducing the pick wear. The results indicated that the cemented carbide pick has the best wear resistance among the three kinds of picks, and the pick life can be significantly extended for picks with a wear-resistant coating surface. It is also found that the pick wear has the highest influence on the normal force. Thermal fatigue and overloading are two factors that cause the pick wear failure. The results can also be used for design the conical pick with wear-resistant coating and validate the numerical models.

Keywords: Rotary Cutting Machine, Pick wear, Cutting force, Wear-resistant coating
1. Introduction

Coal has been one of the most extensively used fuels for power plants. An imbalance in the excavate ratio has been a major obstacle in the safe and efficient production of coal. With the increase of rock hardness, various problems, such as pick wear and component failure, have become an obstacle for efficient and continuous operations. In addition, the mechanical properties of cutter heads for rock crushing and the wear mechanism of picks should be accurately assessed to improve the cutting performance of roadheaders. The working condition of pick is often severe, complex, and dynamic in nature. Picks usually work under high-impact and high-stress conditions, resulting in frequent failure. The failure modes include premature wear, carbide tip drop off, fracture, and normal wear.

The cutting load acting on the pick have been investigated via simulations and experiments to study the wear of picks in the process of rock cutting. In simulations, the finite element method and discrete element method (Zhou and Lin 2013; Jaime et al. 2015; Rojek et al. 2011; Van Wyk et al. 2014; Lin et al. 2017; Park et al. 2018) are used to explore the mechanical behavior of picks and the critical failure modes of rock fracture. In experiments, several tests of pick wear on different types of equipment are conducted (Gong et al. 2016; MacGregor et al. 1990; Rogers and Roberts 1991; Dogruoz et al. 2015; Liu et al. 2017; Park et al. 2018; Katiyar et al. 2016; Shao et al. 2017; Konyashin and Ries 2014). MacGregor et al. (1990) compared the performance of buttons and conical picks based on data obtained from underground field trials, laboratory tests, and metallographic examinations. Large cutting forces associated with worn picks have caused the vibration increased of a continuous miner. Rogers and Roberts (1991) suggested that a composite mechanism is involved in tool wear and observed that abrasion, impact loading, and frictional heating play an interlinked part in the wear and ultimate destruction of the cutting tools. Full-scale cutting tests in different types of sedimentary rocks with bits having various degrees of wear have been conducted to evaluate the influence of bit wear on cutting forces and specific energy. Studies have examined the relationship of the amount of wear represented by the size of wear flats at the tip of bits, cutting forces, and specific energy (Dogruoz et al. 2015). Liu et al. (2017) also investigated the influence of the cutting types, structures, and working angle parameters on pick wear and the effect of wear on the cutting performance by using an experimental apparatus. On a lab-scale linear cutting machine, three samples have been tested in terms of different strengths, and the cutting forces have been measured and used to calculate the specific energy. The relation between the structural stability and durability has also been discussed in terms of resultant force and skew angle (Park et al. 2018). Katiyar et al. (2016) analyzed the failure modes, including abrasive wear, erosion failure, corrosion or dissolution action, fracture, thermal cracking action, and thermal deformation, of tungsten carbide bits. CSIRO developed an abrasive-resistant tool. Tests based on Taguchi’s L25 orthogonal array have also been conducted to analyze the cutting parameters of a linear rock cutting planer (Shao et al. 2017). The performance tests of cemented carbides with different WC grain sizes in rock cutting have been carried out on a cutting machine, and the wear damage, behavior, and mechanisms of cemented carbides have been examined (Konyashin and Ries 2014). The worn out parts of the conical pick have been examined using scanning electron microscopy (SEM) and energy dispersive X-ray (EDX) point analysis by some researchers, some different types of wear mechanisms were observed in different tool samples (Deng et al. 2011; Dewangan et al. 2014; Dewangan and Chattopadhyaya 2015). Although the wear of picks has been widely explored, the severe abrasive wear of the cemented carbide picks
limits the usage of machinery in hard rock mines.

In this study, three picks with different tip materials were tested using a full-scale rotary cutting machine to examine the wear mechanism of the picks. We aim to find a method that could effectively improve the wear resistance. The cutting load, mass loss, and temperature variation of the three picks were compared, and the wear characteristics and temperature distribution of the picks were analyzed. The influence of the pick wear on the cutting performance is investigated to provide an experimental guideline for reducing the wear.

2. Experimental method

2.1 Full-scale rotary cutting machine (RCM)

The test is performed on a full-scale rotary cutting machine, which is the most advanced single-pick rotary cutting machine in currently, at the National Engineering Laboratory of Coal Mining Machinery and Equipment. This machine consists of a test platform, a control system, a test system, and data analysis software. The structure of the test platform is shown in Fig. 1, and the static contact of pick-rock is shown in Fig. 2. The device can immediately monitor the cutting load, vibration, temperature, and dust amount during the tests. The largest size of the rock sample that it can be accommodated is 1400 mm × 800 mm × 600 mm. The rock is clamped with a special fixture to prevent it moving under the large impacts. The test system comprises an octagonal ring dynamometer, a multi-channel high-precision data acquisition system, and a wiring board. The sampling frequency is up to 20 kHz. The rock cutting surface should be first trimmed to ensure that the relative position of the pick and rock is consistent during the cutting process.

2.2 Experimental scheme

The test was performed using three kinds of conical picks with different tip materials. The wear area, wear volume, and wear height were compared. Three components of the cutting load during the asymptotic wear of the pick were monitored. The influence of the picks with different wear degree on the cutting load were analyzed. A FLUKE handheld infrared camera was used to record the temperature change of the pick during the rock cutting.

Generally, the pick is made up of the alloy steel pick body and cemented carbide pick tip, so the material of the pick tip and pick body is taken as the research object. Three conical picks with the same geometry and different tip materials were used (Fig. 3) to investigate the wear resistance of the pick tip and the influence of different wear degrees on the cutting load. The first one was the cemented carbide (CC) pick (Model P5MS-3880-1762), which is suitable for cutting rocks with ordinary hardness. The second one was alloy steel (AS) pick, which is composed of high-strength 35CrMnSiA steel. The third one was an AS pick with wear-resistant coating (ASWRC), whose hardfacing process was utilized to prepare a nickel-based wear-resistant coating on the AS pick tip. The Vickers microhardness of the three kinds of picks was determined as 1380, 862, and 1025 HV by using the OU2200 hardness tester, respectively. In this experiment, natural sandstone (1200 mm × 800 mm × 600 mm) was selected as the rock sample. The mechanical properties of the sandstone were shown in Table 1. During the entire test, the cutting speed was 1.47 m/s, the cutting depth was 4 mm, the cutting line spacing was 12 mm, and the attack angle was 50°. Based on the width of rock sample and the cutting line spacing, the pick involved in rock cutting from left to right was 70 cycles.

2.3 Data acquisition
Leap-forward fracture is an obvious characteristic in the process of rock cutting. The signal acquisition system was used to record the cutting load applied to the pick for each cutting cycle. Fig.4 shows the cutting load curves of the CC pick at the 49th cutting cycle, each peak point corresponding to a leap-forward crushing process. The test data shows that the interaction time between the pick and rock lasted approximately 325ms, and the horizontal line was the mean value of each component of the cutting load.

3. Results and discussion

3.1 Wear degree of the picks

The impact load between the pick and rock was high, and the wear area near the pick tip increased gradually under the interaction of friction and heat. The quality and height of the pick were measured before and after the test. The quality losses of the CC, ASWRC, and AS picks were 1.2, 3.6, and 4.6 g, respectively. The percentages of the loss were 0.07%, 0.22%, and 0.28%, respectively. Moreover, the losing heights were 0.45, 0.81, and 1.09 mm, respectively (Table 2). Fig.5 illustrates the wear degree of pick after the test. The comparison results of the pick wear before and after the test revealed that the wear area of the CC pick was small, and its wear resistance was remarkably higher than the other picks. In comparison with the AS pick, the ASWRC pick was protected by the wear-resistant coating in the early stage of the test, and its wear area expanded slowly. As the cutting cycle increased, the wear area expanded, and the protective effect of the wear coating was gradually lost. After the 40th cutting cycle, the wear speed of the ASWRC pick and AS pick tended to be consistent. In general, the CC tip was welded to the AS pick body. After the CC tip fell off, the pick body was directly involved in the rock cutting, and a sharp wear phenomenon occurred. When the overhanging part of the pick was welded with better wear-resistant coating, the wear rate of pick and the damage rate of cutter head were decreased.

3.2 Influence of different wear degrees on the cutting load

The decomposition of the cutting load acting on the pick is shown in Fig.6, where \(d\) is the cutting depth, \(\delta\) is the attack angle, \(n\) is the cutting speed, and we make the following provisions: The component force acting on the pick opposite to the direction of motion is defined as the cutting force \((F_c)\), the component force perpendicular to the movement direction of pick tip is defined as the normal force \((F_n)\). According to the right hand rule, the component force from the normal force turn to the tangential direction is defined as the lateral force \((F_s)\).

During the test, the tool holder and rock were kept in a constant relative position. The pick wear increased the distance between the pick tip and the cutting surface, and the corresponding cutting depth became small. The failure type of rock under the action of pick was leap-forward fracture. The formation of small rock chips and the spallation of large rock chips were occurred alternately, and the change of the cutting load corresponds to the geometric size of rock chips. Therefore, the mean value of the cutting load can reflect the stress state of pick during the rock cutting process better. Test data was recorded once per cutting cycle. The mean value of each component force is calculated for each cutting cycle, and every piece of data is taken every two cutting cycle for linear fitting analysis. Fig.7 shows the trend of the mean component force varying with the cutting cycle for three picks. The pick wear had the greatest influence on the normal force, whereas the cutting force and lateral force were slightly fluctuated.
The trend of the normal force showed that the CC pick and ASWRC pick initially decreased and then increased as the cutting cycle increased. The normal force of the AS pick decreased and gradually became stable as the cutting cycle increased. The relation of the normal force was \[ F_{\text{CCpick}} < F_{\text{ASWRCpick}} < F_{\text{ASpick}} \]. The results showed that the cemented carbide tip had good abrasion resistance, and the abrasion area expanded slowly for the CC pick. Before the 35th cutting cycle, the pick tip was slightly worn, and the cutting depth at this stage elicited a dominant influence on the cutting load. Hence, the cutting load decreased as the cutting depth decreased. With the accumulation of the local temperature of pick, its wear was intensified, and the wear surface expanded rapidly under the combination of heat and friction. At this stage, the influence of the wear area on the cutting load was dominant, and the cutting load increased as the wear surface increased. For the ASWRC pick, the protective effect of the wear-resistant coating resulted in a slow wear rate of the pick tip in the early stage. Similarly, the wear of pick intensified as the temperature increased. The wear-resistant coating around the wear surface continued to play a protective role. Hence, the trend of the cutting load was consistent with the CC pick. Furthermore, the wear rate of the AS pick tip was sharply increased from the beginning of rock cutting. The cutting load decreased as the cutting depth decreased. The test result indicated that the wear areas produced were evident at the sixth cutting cycle. With regard to the mean normal force, due to the severe wear of the AS pick, it was larger than the CC pick and ASWRC pick, which were 16% and 25%, respectively.

The results showed that the material of pick tip and pick body played an important role in the wear resistance of the picks. Despite the effects of working parameters on wear characteristics, these parameters were difficult to control. Without affecting the structure design of the pick, to improve its wear resistance, the tapered part of pick can be laser coating by using tungsten carbide, nickel- and iron-based wear-resistant materials.

### 3.3 Temperature analysis of the pick with various wear areas

The front angle made the pick crush the rock at a certain attack angle, and the pick moved down. Hence, the pick was impeded by the cutting force. The posterior angle made the pick and cutting surface in a state of friction, thereby causing the abrasion marks. Moreover, the positive pressure of the friction was provided by the normal force, and resulting in pick wear and temperature change.

The temperature distribution characteristics were analyzed using the FlukeTi100 infrared thermal imager, which recorded the temperature changes of the three kinds of picks during the cutting process. Each cutting cycle was recorded using a camera mounted inside the device. In Fig.8, the recorded images did not show a noticeable spark for the CC pick, but the AS pick produced an obvious spark in the initial stage, and the ASWRC pick had a clear spark in the later stage.

The sharp friction occurred at the front end between the pick and rock, especially in fine sandstone. High temperature caused by friction accelerated the damage of pick. The distribution of temperature differed greatly when the rock was cutted by the pick with different materials. The CC pick caused the minimum environment temperature (i.e., 113.6 °C), whereas the AS pick resulted in the highest environment temperature (i.e., 445.9 °C), as shown in Fig.9.

Under the condition of the intermittent impact load, the hard microconvex points on the surface of pick were deformed. The plastic flow caused by the repeated extrusion was produced near the
soft surface. It accumulated at the subsurface layer of the pick. The high temperature produced by
the friction heat on the worn surface of pick tip was transmitted to the entire pick body quickly.
The rotation of pick was a periodic rotary motion in rock cutting. The temperature increased when
the pick contacted with the rock and decreased when it left the rock. The alternating temperature
causd the high-temperature tempering at the top of pick. Hence, the tempered sorbite was
generated. The hardness of pick was critically decreased, and the pick wear was accelerated.

The AS material had low hardness and poor abrasion resistance, and its hardness decreased
under the influence of high temperature during the cutting process. Therefore, when the pick body
wore out, the cemented carbide pick tip lost its support body and fell off, resulting in the rapid
failure of pick. The surface of the AS pick was welded the Ni-based wear-resistant coating using
the technology of laser overlaying. The results showed that the wear-resistant coating had a good
protective effect on the AS body. Therefore, surfacing the wear resistant coating at the conical part
of the CC pick was necessary to extend its life.

4. Conclusion

The experimental studies have been conducted on the full-scale rotary cutting machine, and the
wear characteristics and temperature distribution of picks have been discussed. Based on the
experimental results, the following conclusions were obtained. a) The CC pick has the best wear
resistance among the three picks, and the pick life can be remarkably extended after the pick body
with wear-resistant coating. b) The pick wear has the highest influence on the normal force,
whereas the cutting force and lateral force slightly fluctuated. c) Thermal fatigue and overloading
are the two factors of the pick wear failure. Therefore, high temperature changes the
microstructure on the surface of pick and decreases the hardness. As a result, the pick is prone to
wear. With the extension of the wear area of pick tip, the pick continuously became overloaded,
and the pick wear was aggravated.

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2018016463)

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doi:10.1007/s00603-015-0734-x.

Fig. 1 Motion diagrammatic sketch of rotary cutting machine
Fig. 2 Actual contact of rock-tool
Fig. 3 Sharp picks used in the tests
Fig. 4 Components of cutting load at 49th cycle varied with time
Fig. 5 Blunt picks after the wearing tests
Fig. 6 Schematic drawing of rock cutting
Fig. 7 Mean forces of three picks varying with the cutting cycle (a) CC pick (b) ASWRC pick (c) AS pick
Fig. 8 Cutting process by picks (a) CC pick (b) AS pick (c) ASWRC pick
Fig. 9 Comparison of sparks produced by three picks in cutting process
**Table 1** Measured rock property

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<tr>
<th>Type of rock</th>
<th>Density (kg/m³)</th>
<th>Uniaxial compressive strength (MPa)</th>
<th>Brazilian tensile strength (MPa)</th>
<th>Elasticity modulus (GPa)</th>
<th>Poisson ratio</th>
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<td>Sandstone</td>
<td>2340</td>
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**Table 2** Variation of mass and height before and after the tests

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<th>Parameters</th>
<th>CC pick</th>
<th>ASWRC pick</th>
<th>AS pick</th>
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<td><strong>Before</strong></td>
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<td></td>
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<td>mass/g</td>
<td>1843.1</td>
<td>1649.4</td>
<td>1650.3</td>
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<td>height/mm</td>
<td>156.28</td>
<td>155.13</td>
<td>155.01</td>
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<tr>
<td><strong>After</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>mass/g</td>
<td>1841.9</td>
<td>1645.8</td>
<td>1645.7</td>
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<tr>
<td>height/mm</td>
<td>155.83</td>
<td>154.32</td>
<td>153.92</td>
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**Fig. 1** Motion diagrammatic sketch of rotary cutting machine

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