Experimental study on the influence of cutter shape on cutter wear for hard rocks

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Abstract: Cutter shape is an important factor on cutter wear for hard rock TBMs. In this paper, the influence of cutter shape on the cutter wear was investigated by the wear tests on small-size cutters with the scale of 1/10 of the actual size, and the related rock fragmentation characteristics induced by different cutters was studied as well. In the tests, 6 types of small-size cutters, considering the design parameters of cutter diameter, cutter tip width and cutter tip shape, were selected. The granite samples were collected from the Beishan site, Gansu province of China. For each test, the cutting distance of the single cutter was 100m, and then the cutter wear could be obtained by weighing method. The tests shown that, 1) the cutter wear was basically proportional to the cutter tip width when the same penetration was reached, while the cutter force was not reduced remarkably for the narrow cutter when compared with that of wide-tip cutter; 2) the wear of 17-inch cutter was much higher when compared with that of 19-in and 20-in cutters; 3) the wear of round-edged cutter was obviously lower than that of flat-edged cutter, due to the former hardly presented curling behaviour after cutting while the latter had obviously curled. The test results facilitated better understanding of wear mechanism of TBM cutters and provided the references for cutter selection for TBM tunnelling in hard rock.

1. Introduction
Cutter wear plays an important role in the TBM tunnelling which directly affects the construction schedule and cost, especially for the TBM projects in hard rock mass[1][2]. The construction of China’s first Underground research laboratory (URL), named Beishan URL, for geological disposal of high-level radioactive waste (HLW) will be constructed in 2021. The preliminary design of the URL project has been proposed, with the main structure of an access ramp, three shafts and two experimental levels. The access ramp is proposed to be excavated by tunnel boring machine (TBM) [2]. The uniaxial compressive strength (UCS) of the rock mass in Xinchang site is 110-235 MPa and the average value is 173 MPa, mostly in the range of 160-180 MPa; the Cerchar tests show that the Cerchar abrasiveness index (CAI) value is 4.3-5.3, which is classified as very high abrasiveness [3]. As cutter consumption is highly related to construction cost and time for hard rocks, it is necessary to conduct cutter selection for the specific geological conditions of Beishan URL project. For cutter selection, one of the most important issue is to understand the influence of cutter shape on the cutter wear for Beishan granite.

A lot of investigations on cutter wear have been conducted in the past decades. Rostami [4] developed a model on the basis of a basic life determined using the CAI index. The NTNU model [5][6]
developed by the Norwegian Institute of Technology used a specialized abrasiveness value (AV) to estimate cutter life. Wang et al. [7] developed a method for predicting disc cutter wear for a hard rock TBM cutterhead by energy analysis. Liu et al. [8] established the relationship among CAI, UCS and the cutter life, and shown that the rock abrasivity index well correlates with cutter life. Su et al. [9] established a disc cutter wear prediction model based on the wear mechanism and motion analysis of the cutter rings, and found there was a linear correlation between the cumulative wear depth and the advance distance. Lan et al. [10] investigated the relationship between wear rate and penetration, rock UCS, thrust based on the Yin Song Project, and a general prediction formula of the wear rate of disc cutters was established. Farrokh [1] developed a new cutter consumption model based on a statistical analysis of a database of the records of 135 TBM projects, and the results show the estimates of proposed new model were in good agreement with the actual values. Due to the large size and high cost of full-size cutters, it is difficult to achieve systematic experimental research in laboratories. To provide better approaches of study on cutter wear in laboratory, Sun et al. [11] developed a composite wear test device model with experimental disc cutters scaled to 1/10 of the actual cutter, and the device model showed reliable performance of cutter wear prediction when compared with Yin Han Ji Wei Project.

In this paper, the composite wear test device model was used to conduct wear test, and the influence of cutter shape on cutter wear for Beishan granite investigate. 6 types of small-size cutters with different diameters, tip widths and tip shapes were tested. The test results provide a basis for the optimal design of the cutter for Beishan URL project.

2. Test design and results

2.1 Test design

The test equipment of composite wear test device model, developed by the State Key Laboratory of Shield and Tunneling Technology [11], was employed in this study, as shown in figure 1. The device model is designed based on the principle of the interaction of rock-cutter, and can be used to obtain the cutter wear, the amount of rock fragmentation, and the cutter force characteristics during the whole test process. The test method is similar to the real situation, and the test results can better reflect the abrasiveness of the rock to the cutting tool.

In this test, 6 types of cutters commonly used in hard rock formations were simulated, and the parameters were shown in the actual engineering cutter type parameters listed in table 1. In the test, the cutter was reduced in a scale of 1/10. The test cutter and its dimensions were shown in figure 2. The rock samples were collected from the drill cores of borehole BSQ02 and BSQ03 of the Xinjiang site of Beishan area, Gansu province of China, and the sample dimension for wear testing was 350mm×60mm×60mm. The core sample and test sample were shown in figure 3. A total of 6 sets of wear tests were conducted. For each set, 3 tests were performed and the cutting distance was 100m for each test. During the test, the cutter force and the related penetration were collected. After the test, the cutter was weighed to calculate the amount of wear.

| No. | Cutter shape (diameter-tip width-tip shape) | Sample dimension (mm) | Penetration P (mm) |
|-----|--------------------------------------------|----------------------|--------------------|
| 1   | 17inch-13mm-flat tip 1.7inch-1.3mm-flat tip | 350×60×60 350×60×60 | 0.05 0.05 |
| 2   | 19inch-13mm-flat tip 1.9inch-1.3mm-flat tip | 350×60×60 350×60×60 | 0.05 0.05 |
| 3   | 19inch-16mm-flat tip 1.9inch-1.6mm-flat tip | 350×60×60 350×60×60 | 0.05 0.05 |
| 4   | 19inch-19mm-flat tip 1.9inch-1.9mm-flat tip | 350×60×60 350×60×60 | 0.05 0.05 |
| 5   | 20inch-17mm-flat tip 2.0inch-1.7mm-flat tip | 350×60×60 350×60×60 | 0.05 0.05 |
| 6   | 19inch-16mm-round tip 1.9inch-1.6mm-round tip | 350×60×60 350×60×60 | 0.05 0.05 |
2.2 Test results

The test results are shown in table 2. Take the test with 1.9-inch-1.6mm-flat cutter as an example, the tested sample and the cutter, and the relationship of force-penetration-time curve are shown in figure 4. The analysis of the influence of different cutter width, cutter diameter, cutter shape and penetration on cutter wear is as follows.
Table 2. Summary of test results.

| No. | Cutter shape (diameter-tip width-tip shape) | Penetration P (mm) | Wear for 100m cutting (mg) | Average value |
|-----|------------------------------------------|-------------------|--------------------------|---------------|
| 1   | 1.7inch-1.3mm-flat tip                   | 0.05              | 8 11 16                  | 11.7          |
| 2   | 1.9inch-1.3mm-flat tip                   | 0.05              | 6 4 5                   | 5.0           |
| 3   | 1.9inch-1.6mm-flat tip                   | 0.05              | 7 7 8                   | 7.3           |
| 4   | 1.9inch-1.9mm-flat tip                   | 0.05              | 10 9 10                | 9.7           |
| 5   | 2.0inch-1.7mm-flat tip                   | 0.05              | 8 7 11                 | 8.7           |
| 6   | 1.9inch-1.6mm-round tip                  | 0.05              | 5 5 5                   | 5.0           |

Figure 4. Photo of tested rock sample and cutter, and force-penetration-time curve of test.
3. Influence of cutter shape on cutter wear for hard rocks

3.1 The influence of different cutter tip width on cutter wear
Figure 5 shows the results of the abrasion test of a small-size cutter with different cutter tip widths under the same penetration. The results show that the cutter wear is basically proportional to the cutter width, and it can be found that the radial wear of the cutters has little relationship with the cutter width. In addition, according to the characteristics of the cutter force, the cutter force is slightly reduced due to the narrowing of the cutter tip. Based on the analysis of the fracture characteristics of the rock sample, it is found that the penetration increases with the decreasing of cutting tip, but the connection of fractures between the two adjacent cuttings is weakened for the narrow-tipped cutter with tip width of 13mm-flat. The results demonstrate that for hard rocks, reducing of cutter tip width can increase the cutter penetration, but immoderate reducing of tip width presents neither an effective way to reduce cutter thrust, nor an effective way to improve the efficiency rock fragmentation, and moreover, it is difficult to reduce the amount of radial wear of the cutter and results in higher TBM downtime for the more frequent cutter change. Therefore, the narrow-tipped cutter with tip of 1.3mm is not recommended for hard rock ground.

![Figure 5. Wear test results of different blade width and small size cutters.](image)

3.2 The influence of different diameters on cutter wear
Figure 6 shows the results of the wear test of different cutter diameters under the same penetration. The results show that, the wear of 1.7in-diameter cutter is much higher than that of larger-diameter cutter for the same cutting distance. Specially for the 1.7in-diameter cutter, the cutter wear gradually increases from 8mg to 16mg when conducting 3 tests in order as shown in table 2. According to the test phenomenon, the tip of 1.7in-diameter cutter is curled up and leads to acceleration of cutter wear, which mainly due to the frequency of contact between 1.7in-diameter cutter and the rock is much higher than that of the larger-diameter cutter, and the material may present the behaviour of fatigue failure. Therefore, it is recommended to use large-diameter cutters as much as possible under high-strength hard rock conditions, which can increase the allowable wear of the cutter and prolong cutter life in order to reduce the downtime for cutter change.
Figure 6. Wear test results of different diameter and small size cutters.

3.3 The influence of different tip shapes on cutter wear

Figure 7 shows the results of the wear test of small-size cutters with different tip shapes under the same penetration. The results show that, the cutter wear of flat-tipped cutter is much higher than that of round-tip cutter. According to the test phenomenon, the flat-tipped cutter has curling after abrasion, while the round-tipped cutter hardly presents curling behaviour after abrasion. Therefore, it is recommended to use round-tipped under high-strength hard rock conditions.

Figure 7. Wear test results of small-size cutters with different cutting edges.

4. Conclusions

The experimental study on the influence of cutter shape on cutter wear for hard rock was investigated by using composite wear test device model with 1/10 scaled cutters in this paper. 6 types of small-size cutters with different cutter diameter (1.3, 1.6, 1.9mm), cutter tip width (1.7, 1.9, 2.0 inches) and cutter tip shape (flat tip, round tip) were selected, and the Beishan granite was collected as the test rock sample. The main conclusions can be summarized as following:
(1) The cutter wear was basically proportional to the cutter tip width when the same penetration was reached, while the cutter force was not reduced remarkably for the narrower cutter when compared with that of wide-tip cutter, which mainly due to the connection of lateral cracks between two adjacent cutting paths was less effective for the narrow cutter.

(2) The wear of 1.7mm-diameter cutter was much higher when compared with that of 1.9mm-diameter and 2.0mm-diameter cutters, which mainly due to the frequency of contact between 1.7in-diameter cutter and the rock is much higher than that of the larger-diameter cutter, and the material may present the behavior of fatigue failure.

(3) The wear of round-tipped cutter was obviously lower than that of flat-tipped cutter, due to the former hardly presented curling behavior after cutting while the latter had obviously curled.

(4) Based on the test results, it is suggested to selected the cutter with moderate tip width to reach high penetration and main wear resistance, as well as the larger cutter to prolong the service time of single cutter and subsequently reduce downtime for cutter change.

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