Study on influencing factors of cutting efficiency for TBM gage cutters by linear cutting test

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Abstract. The gage cutter is the key component in a tunnel boring machine (TBM); this part affects the machine’s cutting efficiency and maintains the tunnel diameter. In this study, a series of rock cutting tests with different parameters (cutting spacing, penetration depth, and installation angle) is conducted using the mechanical rock fragmentation experimental platform of Beijing University of Technology to study the influences of these parameters on the rock-breaking performance of a TBM gage cutter. During the tests, the triaxial cutting forces and rock chips are collected and analyzed. The test results show that the average normal force of the cutter will decrease with the installation angle increasing at the same penetration depth and cutting spacing, but the average rolling force has the opposite change tendency. The side force is influenced by the installation angle significantly. The side force of the gage cutter plays a more important role in the rock fragmentation than does the side force of the normal cutter. Moreover, the cutting efficiency of the normal cutter is higher than that of the gage cutter. An inclined disc cutter is more conducive to producing rock chips under a large cutting spacing than is a vertical disc cutter, and the optimal cutting spacing under different installation angles is different. This study can provide a reference for TBM gage cutter design and TBM operation parameter optimization.

1. Introduction

Hard rock tunnel boring machines (TBMs) are widely employed in tunnel engineering due to their numerous advantages, such as remarkably high advance rates, safety, and minimal disturbance of the surrounding rock and environment.

TBM excavation relies on the interaction between the machine’s disc cutters and the rock[¹]. Many studies have been conducted on the tool–rock interaction through theoretical, experimental, and numerical methods²–⁶. However, existing studies only focus on the performance of normal cutters. Only a few papers examine the gage cutter, which is installed on the periphery of the TBM cutterhead and also a vital component that affects the advance rate and maintains the tunnel’s outer contour. Because of its special installation site and working condition, a gage cutter has a higher rotation speed and longer cutting length than does a normal cutter. Furthermore, the installation angle, which lies between the gage cutter indentation direction and the TBM advance direction, makes the tool–rock interaction mechanism quite different from that of a normal cutter. An analysis of field data collected from the Åspö underground laboratory disposal pit project showed that the average normal force loading on gage cutters is evidently less than that on normal cutters⁷. These results were validated by test data measured from Entacher’s Koralm Tunnel project⁸.

A series of theoretical and numerical models for the cutting force and cutting efficiency of gage cutters...
was built by Yang and Xia to study the rock fragmentation process\textsuperscript{[9,10]}; they found that tensile failure is the main reason for crack initiation and propagation under gage cutter indentation, and an increasing installation angle leads to a larger cutting force on the gage cutter. Lin\textsuperscript{[11]} established a numerical model for gage cutters to investigate the influence of various parameters, such as angle inclination, cutter radius, blade edge angle, and penetration depth, on cutting efficiency. Huo\textsuperscript{[12]} proposed a theoretical load prediction model of the multistage rock breaking process for gage cutters. Zhang\textsuperscript{[13]} used a numerical stimulation method to analyze the kerf shapes produced by normal cutters and gage cutters; findings showed that the former kerf shape is symmetrical, whereas the latter is asymmetrical. However, there are a few limitations in using theoretical and numerical methods in defining rocks’ material property and failure criterion due to the isotropy and homogeneity of hypotheses. Hence, full-scale rock cutting tests that adopt full-scale disc cutters and actual rock specimens are being extensively conducted in laboratories to study the tool–rock interaction. Using the mechanical rock fragmentation experimental platform of Beijing University of Technology, several groups of linear cutting tests were conducted by Yao\textsuperscript{[14]} to explore the effect of the installation angle and cutting time on the fragmentation patterns of normal and gage cutters. Geng\textsuperscript{[15]} used a rotary cutting machine to analyze the cutting performance of gage cutters with different installation angles.

In this study, several series of linear cutting tests for granite are conducted using a mechanical rock fragmentation experimental platform to investigate the influence of different parameters, such as installation angle, penetration depth, and cutting spacing, on the cutting efficiency of gage cutters. During the tests, the cutting forces are monitored, and rock chips are collected. Then, the specific energy for different cutting conditions is calculated and analyzed.

2. Laboratory tests

2.1. Apparatus

The mechanical rock fragmentation experimental platform of Beijing University of Technology consists of mechanical, hydraulic, automatic control, and data acquisition systems\textsuperscript{[16]}, as shown in Fig. 1. A constant cross-section disc cutter with a diameter of 432 mm is used in the tests. The cutting force loading on the disc cutter includes normal, rolling, and side forces (Fig. 2). The cutting forces can be measured and recorded simultaneously by the data acquisition system at an acquisition frequency of 100 Hz. A constant speed of 20 mm/s is taken as the linear cutting velocity for the tests.

Five Beishan granite rock specimens measuring 1000 mm × 1000 mm × 600 mm are used in the tests (Fig. 3). The physical and mechanical properties of Beishan granite are listed in Table 1.

In this study, the disc cutter is affixed on the cutter mount, which has two types: vertical and inclined. When installed in the vertical mount, the disc cutter can be seen as a normal cutter with an installation angle of 0°, as shown in Fig. 4(a). When the disc cutter is affixed on the inclined cutter mount, the installation angle can be set as 20° and 30°, as shown in Fig. 4(b). Thus, linear cutting tests for gage cutters with installation angles of 20° and 30° can be conducted in the laboratory. An installation angle greater than 30° cannot be studied in the tests due to the limitation of the test equipment.

Figure 1. Mechanical rock fragmentation experimental platform (1- steel framework; 2- triaxial force sensor; 3- cutter mount and disc cutter; 4- specimen box; 5- sliding rail).
Figure 2. Cutting force loading on the disc cutter.

Figure 3. Beishan granite specimen for the linear cutting test.

Figure 4. Installation of TBM cutter for the linear cutting test: (a) normal cutter; (b) 20° gage cutter.

Table 1. Physical and mechanical properties of Beishan granite.

| Parameters                        | Unit   | Value  |
|-----------------------------------|--------|--------|
| Density                           | g/cm³  | 2.60   |
| Elastic modulus                   | GPa    | 23.01  |
| Poisson’s ratio                   | —      | 0.18   |
| Uniaxial compressive strength    | MPa    | 105.06 |
| Brazilian tensile strength       | MPa    | 6.43   |
2.2. Test design

Two cutting spacings (60 mm, 70 mm), three installation angles (0°, 20°, 30°), and several groups of penetration depths are established to investigate the influence of the cutting spacing, installation angle, and penetration depth on gage cutters’ rock cutting efficiency. The linear cutting test is firstly conducted at the penetration depth of 0.5 mm, and then, the penetration depth gradually increases at 0.5 mm intervals. Due to some inevitable factors, such as contact between the rock surface and the blade ring of the disc cutter and the bolts on the side of the cutter mount when the penetration reaches a sizable depth, the maximum penetration of the gage cutters for tests 3 to 5 is set to be smaller than that of normal cutters for tests 1 or 2. The specific parameters of the linear cutting test are listed in Table 2.

| Test number | Installation angle (°) | Cutting spacing (S/mm) | Penetration depth (P/mm) |
|-------------|------------------------|------------------------|-------------------------|
| 1           | 0                      | 60                     | 0.5, 1, 2, 3, 4, 5, 6    |
| 2           | 0                      | 70                     | 0.5, 1, 2, 3, 4, 5, 6    |
| 3           | 20                     | 60                     | 0.5, 1, 1.5, 2, 2.5, 3, 3.5 |
| 4           | 20                     | 70                     | 0.5, 1, 1.5, 2, 2.5, 3, 3.5 |
| 5           | 30                     | 60                     | 0.5, 1, 1.5              |

2.3. Test procedure

The linear cutting test procedure in this study can be summarized as follows:
- The TBM cutter is affixed on the vertical or inclined cutter mount according to the test design.
- The rock specimen is affixed in the specimen box by exerting 0.5 MPa biaxial confining stress on the specimen side surfaces to eliminate relative displacements between the rock and the box during the cutting process.
- The free surface of the rock specimen is pretreated before the test by cutting at a penetration depth of 0.5 mm to represent the actual TBM excavation tunnel face with cutting grooves.
- The cutting forces are recorded during the test (normal, rolling, and side forces), and the rock chips formed during the tests are collected after the completion of each cutting layer. Subsequently, sieve tests are performed on the rock chips to analyze their distribution and shape characteristics.

2.4. Experimental phenomenon

The cutting forces from the different penetration depths are monitored during the tests for the normal and gage cutters, as shown in Figs. 5–7. The normal, side, and rolling forces are recorded individually. The force curves in these figures are the middle segments of the original curves. At the initial or end of the cutting process, the rock failure under the disc cutter is influenced by the artificial rock free surface. Thus, the force loading on the disc cutter is much smaller than actual cutting forces. These phenomena were studied by Xia[17]. Hence, these figures reflect only 30 seconds of the cutting process.

In these figures, the curves of the cutting forces fluctuate with the cutting process continuously. The normal force gradually increases with the indentation process of the cutter. As rock chips form under the cutter, the normal force drops dramatically, accompanied with the rock stress release. As the penetration increases, the change frequency and fluctuation of the normal force become increasingly drastic in both the normal and gage cutters. The amplitudes of the normal, side, and rolling forces increase as well. However, the amplitude of the side force loading on the gage cutter is dramatically greater than that on the normal cutter. This indicates that the side force of the gage cutter plays a more important role in rock fragmentation than does the side force of the normal cutter.
Figure 5. Cutting forces of the normal cutter with different penetration depths.

Figure 6. Cutting forces of the 20° gage cutter with different penetration depths.

Figure 7. Cutting forces of the 30° gage cutter with different penetration depths.

After a layer of cutting, rock chips and rock ridges between the neighboring grooves are formed on the cutting surface. The representative rock surfaces after cutting with the 20° gage cutter are shown in Fig. 8.

Some large typical rock chips produced in the tests are shown in Fig. 9. In these figures, the size of each grid in the background is 5 cm × 5 cm, and rock chips longer than 5 cm are exhibited. With a low penetration depth, such as 0.5 mm and 1.0 mm, the force curves of the normal cutter all fluctuate at a low frequency with a few rock chips forming, as shown in Fig. 9(a). On the contrary, only some slags are formed during the tests at the penetration of 0.5 mm for the gage cutter, as shown in Figs. 9(d) and (g). With the penetration depth increasing, the cutting forces fluctuate sharply and frequently at the penetration depth of 2.0–4.0 mm for the normal cutter. Meanwhile, longer but thinner rock chips
appear. For the gage cutter at the penetration of 1.0–3.0 mm, large rock chips appear in large quantities, with the curves of the cutting forces fluctuating more sharply than before. However, for the 20° gage cutter tests, the size of the rock chips exhibits a considerable increment as the cutting spacing changes from 60 mm to 70 mm, especially at a larger penetration depth, as shown in Figs. 9(e), (f), (h), and (i). For the normal cutter, when its penetration depth reaches 5 mm, the number of short but thick rock chips and the proportion of grinded rock powders increase dramatically. Moreover, the cutter vibrates intensively, and the curves of the cutting forces fluctuate more acutely. Under this condition, the rock specimen is overcrushed by the TBM cutter. Similar phenomena occur during the gage cutter tests at the penetration depth of 3.5 mm.

![Figure 8](image-url)  
**Figure 8.** Typical rock surface after 20° gage cutter cutting. (a)–(c) Cutting spacing of 60 mm and penetration of 0.5 mm, 1.0 mm, and 2.0 mm; (d)–(f) cutting spacing of 70 mm and penetration depth of 0.5 mm, 1.0 mm, and 2.0 mm.
Furthermore, the horizontal component of the force applied is approximately symmetric to the phenomena of rock chips enlargement. As the spacing increases, the variation and under the installation angle of 20°. The relationship between the cutting forces and installation angles under the different test parameters is shown in Fig. 10. Findings show that the normal forces all reach a relative minimum at the installation angle of 20°. As a result of the function of the cutter edge, the indentation mechanism of the gage cutter is quite similar to that of a V-shaped disc cutter. The normal force drops considerably under this condition. When the installation angle reaches 30°, the contact area between the cutter edge and the rock increases again, and the normal force grows correspondingly. However, the variation in the side force is quite different from that in the normal force. As shown in Fig. 10(b), the side force increases dramatically with the installation angle. Specifically, a 40× enlargement is observed from the normal cutter to the gage cutter at the installation angle of 20°. The rock chips appear to be distributed uniformly and randomly on both sides of the cutting grooves under the normal cutter, but they nearly concentrate on one side of the gage cutter inclination. These phenomena reveal that the rock stress distribution and the dense core under the normal cutter are approximately symmetric along the vertical direction. Moreover, they concentrate on the side where the gage cutter inclines to. Therefore, the side force loading on the gage cutter can be considered the horizontal component of the force applied from the cutter to the rock. The rolling forces increase slowly with the installation inclination, as shown in Fig. 10(c).

Furthermore, the cutting spacing has a slight influence on the cutting forces both in the normal and gage cutters. As the spacing increases from 60 mm to 70 mm, the cutting forces (normal, side, and rolling forces) all exhibit finite growth.

### Table 3. Average cutting forces for the linear cutting tests.

| Cutter type | Penetration depth (mm) | Normal force (kN) | Side force (kN) | Rolling force (kN) |
|-------------|------------------------|-------------------|-----------------|-------------------|
|             |                        | S=60mm S=70mm     | S=60mm S=70mm   | S=60mm S=70mm     |
| Normal cutter | 0.5   | 96.96 | 87.94 | 0.25 | 0.39 | 2.64 | 2.36 |
|             | 1.0   | 123.17 | 132.87 | 0.64 | 2.31 | 4.58 | 5.91 |
|             | 2.0   | 146.76 | 165.95 | 1.24 | 3.31 | 8.65 | 11.73 |
|             | 3.0   | 163.54 | 180.96 | 0.91 | 5.63 | 12.50 | 16.41 |
|             | 4.0   | 183.96 | 203.70 | 1.56 | 6.82 | 18.62 | 23.31 |
|             | 5.0   | 186.85 | 206.56 | 1.19 | 10.94 | 25.44 | 28.41 |
|             | 6.0   | 194.95 | 219.38 | 1.28 | 9.80 | 29.61 | 37.09 |
|             | 0.5   | 77.96 | 77.31 | 21.56 | 18.47 | 2.53 | 3.07 |
|             | 1.0   | 110.18 | 118.58 | 25.49 | 23.42 | 5.50 | 6.57 |
|             | 1.5   | 120.56 | 128.67 | 24.31 | 24.46 | 7.50 | 8.08 |
|             | 2.0   | 131.09 | 136.61 | 22.03 | 24.44 | 10.03 | 10.57 |
3.2. Analysis of cutting efficiency

Specific energy (SE) is a vital index for evaluating the cutting efficiency of TBM cutters; it represents the energy consumption of the breaking unit volume of rocks. SE can be calculated by the following equation:

$$SE = \frac{F_r \times L}{V}$$,

where $F_r$ is the average rolling force, $L$ is the length of the cutting track, and $V$ is the volume of rock chips and calculated by the ratio of the rock chips’ mass to their density. The lower the SE, the less energy is consumed to break a unit volume of rock. This index directly reflects the excavation efficiency of TBM cutters. The SE for the different tests is calculated and listed in Table 4.

Table 4. Specific energy for the different cutting tests.

| Cutter type | Penetration depth (mm) | Specific energy (MJ/m³) |
|-------------|-------------------------|-------------------------|
|             | S=60mm                  | S=70mm                  |
| Gage cutter | 0.5                     | 79                       | 130                     |
|             | 1.0                     | 75                       | 91                      |
|             | 2.0                     | 77                       | 89                      |
| Normal cutter | 3.0                 | 88                       | 98                      |
|             | 4.0                     | 109                      | 122                     |
|             | 5.0                     | 130                      | 123                     |
As shown in Fig. 11, there is a similar relationship between the normal cutter and the gage cutter. The SE decreases firstly and then grows with the penetration depth. It approaches the minimum at a penetration range of 1.0–2.0 mm.

As shown in Figs. 11 and 12, with an increase in the installation angle, the SE also increases. Therefore, the cutting efficiency of the normal cutter is higher than that of the gage cutter, especially under the 60 mm cutting spacing. Hence, increasing the installation angle will adversely affect the cutting efficiency. Additionally, an increase in the cutting spacing will increase the SE for the normal cutter at different penetration depths. By contrast, with the cutting spacing growing from 60 mm to 70 mm for the 20° gage cutter, the SE distinctly drops at larger penetration depths, such as 1.0 mm, 2.0 mm, and 3.0 mm, as shown in Figs. 12(b), (c), and (d). This indicates that enlarging the cutting spacing, especially at large penetration depths for the gage cutter, is beneficial to the cutting efficiency. These test phenomena reveal that, for the 20° gage cutter tests at the penetration of 1.0–3.0 mm, rock debris remains on the rock surface whose proportions of small chips and powders at the cutting spacing of 60 mm are higher than that at the cutting spacing of 70 mm (Fig. 8). This is validated by Figs. 9(c), (f), (h), and (i), where either the size or proportion of large chips under the 70 mm cutting spacing is greater than that under the 60 mm cutting spacing. This specific phenomenon indicates that it is easier to cause excessive cutting at the cutting spacing of 60 mm, where considerable cutting energy is consumed to grind the rock into powder, rather than to produce large rock chips. By contrast, when the cutting spacing reaches 70 mm, most of the energy is consumed efficiently to form large rock chips. Thus, the cutting efficiency is relatively higher.

![Figure 11. Curves of SE versus penetration under different cutting parameters.](image-url)
3.3. Sieve test results and analysis

The rock chips produced by the different tests are sieved to obtain sieve curves. The results of the sieve tests for the different installation angles are illustrated in Fig. 13. The cutting efficiency for the different tests can be validated by these sieve curves.

In Fig. 13, the sieve curves for the normal cutter at different penetration depths at both cutting spacings (60 mm and 70 mm) are more convergent than those for the 20° gage cutter. In other words, at the same cutting spacing, the proportions of the rock powders and chips in the normal cutter tests are approximated more at the different penetration depths. However, that proportions for the gage cutter tests are quite different. This phenomenon illustrates that the rock cutting efficiency of gage cutters is more sensitive to penetration than is the efficiency of normal cutters.

For the normal cutter tests, when the cutting spacing is 60 mm (Fig. 13(a)), the sieve curve at the penetration depth of 1 mm indicates that the proportions of the large rock chips are higher than those of rock powders. Thus, most of the cutting energy is used to form rock chips rather than grind powders extremely; consequently, the cutting efficiency in this case is the highest. With the cutting spacing increasing to 70 mm (Fig. 13(b)), the optimal penetration depth changes from 1 mm to 2 mm, according to the chip–powder proportions. These conclusions are identical to the SE results in Fig. 11.

A comparison of Figs. 13(c) and (d) shows that, for the 20° gage cutter at the cutting spacing of 70 mm, the sieve curves at all penetration depths are flatter than those at the cutting spacing of 60 mm. Moreover, the curves become much steeper when the sieve hole diameter is within the range of 31.5–50 mm. Therefore, the proportions of large rock chips whose dimensions are larger than 31.5 mm at the cutting spacing of 70 mm are more than those at the cutting spacing of 60 mm. In other words, the rock cutting tests under the cutting spacing of 60 mm produce more powders and smaller rock debris.

The cutting efficiency under the cutting spacing of 70 mm is then higher compared with that under 60 mm.

Figure 12. Effect of installation angle and cutting spacing on SE.
4. Conclusions

The cutting force loading on both the normal and gage cutters fluctuates during the cutting process continuously. With changes in penetration depth or cutting spacing, the cutting force loading’s variation frequency, range, or amplitude also changes accordingly. With the penetration depth increasing, the fluctuation range or frequency of the normal force changes much more dramatically and rapidly both in the normal and gage cutters. The amplitudes of the normal, side, and rolling forces all increase as well. However, when the installation angle grows, the variation tendency of the cutting forces becomes significantly different. The normal force reaches a relative minimum at the installation angle of 20°. Meanwhile, the side force is influenced by the installation angle significantly. The tool–rock interaction mechanism experiences a distinct transformation from the normal cutter to the gage cutter. Thus, the side force loading on the gage cutter exhibits a nearly 40× increment compared with that on the normal cutter. The influence of the installation angle on the rolling force can be negligible. Additionally, increasing the cutting spacing slightly enhances the cutting forces.

The SEs of both the normal and gage cutters decline firstly and then grow with the penetration depth. The SE approaches its relative minimum at a penetration range of 1.0–2.0 mm, which is the optimal penetration depth for Beishan granite. With a growth in the installation angle, the SE increases at the same penetration depth, especially under the 60 mm cutting spacing. Therefore, the cutting efficiency of the normal cutter is higher than that of the gage cutter due to the special rock chip formation pattern under the gage cutter. For the normal cutter, increasing the cutting spacing will adversely affect the cutting efficiency. By contrast, particularly at a large penetration, increasing the cutting spacing will improve the cutting efficiency of the gage cutter, given that the gage cutter applies considerable horizontal load to the rock, which facilitates the excessive rock breaking under a small cutting spacing. In other words, increasing the cutting spacing at a large penetration will enhance the cutting efficiency of the gage cutter.

Figure 13. Sieve test results under different cutting parameters.
Acknowledgments
This work is supported by a grant from the General Research Program of Beijing Municipal Education Commission (Grant No. KM20171005033).

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