Comparative Study on Rock Breaking Performance of Flat-Top Rolling Cutters and Toothed Rolling Cutters Based on Numerical Simulation

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Abstract. Shield tunneling machines are powerful tools for underground transportation construction, but working in hard rock environments can exacerbate the wear and tear of their rolling cutters. In recent years, the rock-breaking performance of toothed rolling cutters has gradually attracted attention. This article conducts numerical simulation research on the rock-breaking process of flat-top rolling cutters and toothed rolling cutters, and compares the effects of hob width and penetration on their rock-breaking performance. The results show that with the continuous increase of width and penetration, the rock-breaking efficiency of the toothed hob and the flat-top hob continues to improve. When the width of the hob is small, the toothed hob has smaller wear and higher rock breaking performance. When the width of the hob is large, the difference in rock breaking performance between the toothed hob and the flat-top hob is not significant. The study on the rock-breaking performance of flat-top rolling cutters and toothed rolling cutters under different excavation parameters has important guiding significance for the selection and improvement of rolling cutters for shield tunneling machines in underground engineering.

Keywords: Gear hobbing cutters, Rock breaking, Excavation parameters, Numerical simulation

1 Introduction

A number of issues, including low efficiency and tool wear, frequently arise when the hob operates in hard rock environments. Approximate theories are typically simplified based on practical engineering while researching the rock-breaking impact of cutting instruments and its influencing components, which has significant limits.[1]. However, the expense of the experiment is significant, and getting the results is a hassle[2,3]. Numerous academics both domestically and internationally primarily employ numerical simulation techniques to investigate how tool and shield tunneling machine operating parameters affect the effectiveness of rock-breaking operations. Hao Yongxing et al.

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used the principle of specific energy for rock breaking to establish the ideal cutting edge angle for rock breaking efficiency at various joint angles[4]. The rock fragmentation ability and specific energy fluctuation of disc cutters with varying disc cutter spacing were examined by Zhang et al[5]. Zhang et al. examined the dynamic features of rock breaking at various penetration rates using a disc-shaped hob[6]. The link between cutting force, speed, and angle during the rock mass-cutting process was determined by Abo. Elnor et al[7]. Gong et al. used multivariate nonlinear regression analysis to study the influence of different rock parameters on the rock breaking effect of shield tunneling machines[8]. Cho et al. studied the influence of the spacing between rolling cutters and the ratio of different hob penetration depths on the volume of rock fragmentation by rolling cutters[9]. Chen et al. investigated the optimal combination of ball toothed and flat toothed hob cutters and penetration under different rock characteristics[10]. Wu et al. found through studying the rock breaking mechanism of the toothed hob that the toothed hob is a "progressive" rock breaking method[11].

In hard rock regions, the flat-top hob's rock-breaking performance is subpar, but the toothed hob performs well under a variety of geological circumstances. In order to numerically simulate the rock-breaking process of toothed and flat-top rolling cutters with varying widths and penetration degrees, this article uses the 17-inch rolling cutters as an example. It then investigates the impact of hob width and penetration degree on the wear degree and rock-breaking performance of rolling cutters.

2 Research on the Rock-Breaking Effect of Rolling Cutters with Different Blade Widths

To investigate the impact of the hob's blade width on its ability to break through rocks, the blade widths were adjusted to 3 mm, 4 mm, 5 mm, 6 mm, and 7 mm, in that order. The toothed hob is shaped like a pick tooth, with 40 of these teeth spaced out around the rolling cutter's perimeter. The hob is fixed as a solid body[12]. The Figure 1 depicts the model.

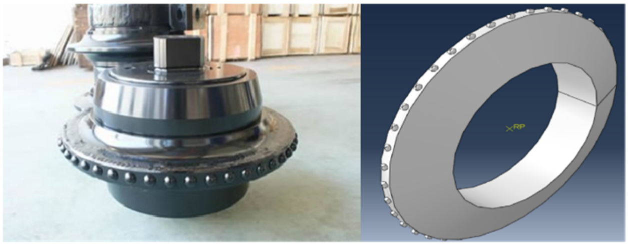

Fig. 1. Schematic diagram of the structure of the inlaid gear hob[12]

The rock's failure conditions are described by the Druker Pager constitutive model with the rock specified to be isotropic. Table 1 displays the rock mechanics performance characteristics. In order to investigate the impact of varying penetration degrees on the rock-breaking effect under the same blade width, the first analytical stage involves simulating the penetration failure of a hob pushing into a rock and varying the hob speed in various models. In various penetration models, the blade width is set to 4 mm, and the first analysis step lasts for 0.2 seconds. The hob's linear velocity is then set to 50 mm/s, with the direction directed along the rock surface, in the second analysis step. All other velocities are set to zero, and the hob can rotate freely in the Z-axis direction. 4.5 seconds is the allotted time for the analysis.

Table 1. Rock materials parameters

Density	Shear stress	Yield stress	Young's modulus	Poisson's ratio	Friction angle	Expansion angle
2.6 kg/m^{-3}	1.5 MPa	37.5 MPa	17.5 GPa	0.3	55°	0.1°

Adjust the hob's blade width to 3 mm, 4 mm, 5 mm, 6 mm, and 7 mm, in that order, with a 5 mm penetration. Determine the volume of rock mass fractured by the toothed and flat-top hobs' blades using the formulas in Table 2. With a rise in blade width, the total volume of rock fragmentation grows steadily, and the toothed hob has a relatively large total volume of rock fragmentation. The toothed hob's total rock-breaking area is somewhat more than the flat-top rolling cutter's due to the presence of cutting teeth, and the extra rock fragmentation produced by the cutting teeth diminishes with increasing blade width. This is due to the fact that the hob's rock-breaking technique gradually shifts from using both the blade and its teeth to using the blade alone when the blade width is high.

Table 2. Rock fragmentation volume of two different types of rolling cutters under different blade widths

Blade width (mm)	3	4	5	6	7
Rock mass fragmentation volume of flat-top hob (mm^3)	16180	17670	19270	28320	41660
Rock fragmentation volume of toothed rolling cutters (mm^3)	18470	18860	19940	29170	42480

Examine the causes of the varying amounts of rock that rolling cutters under various blade widths shattered, as well as the wear on the blades. Figures 2 (a), 3 (b), and 3 (c) depict the rolling cutters' lateral force, vertical force, and rolling force curves for varying blade widths. Only the blade widths of 3 mm, 5 mm, and 7 mm are given here for convenience of observation. The load carried by the hob per unit time at various penetration degrees may be calculated by integrating the lateral force, vertical force, and rolling force that it experiences while operating and multiplying the results by the entire working time, as illustrated in Figure 3 (d).

Figure 2 illustrates how the force on the disc hob grows steadily at first, then abruptly drops as it reaches the rock's strength limit, and then circulates periodically, exhibiting periodic variability overall. Additionally, the disc cutter's lateral force is negligible because it is believed that the rock mass is homogenous and isotropic. The hob's rolling and vertical forces rise as the blade's breadth increases, and the blade's wear increases along with it. Simultaneously, the disc cutter's lateral force is less dependent on the blade's breadth. This is due to the fact that the hob's lateral force is mostly determined by the friction that exists between the rock mass and the cutter body. The lateral force remains relatively constant as the hob width increases because there is no increase in the area of contact between the cutter body and the rock mass. Furthermore, it is evident that the disc cutter experiences more wear as the penetration degree increases since the vertical force acting on it grows more than the lateral force.

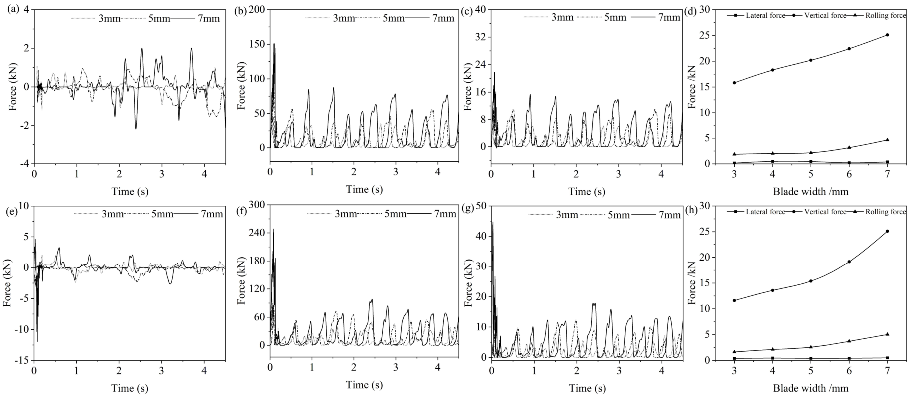

Fig. 2. The (a) lateral force, (b) vertical force, (c) rolling force, and (d) unit time load experienced by flat-top rolling cutters with different blade widths, as well as the (e) lateral force, (f) vertical force, (g) rolling force, and (h) unit time load experienced by toothed rolling cutters

3 Research on the Rock-Breaking Effect of Rolling Cutters with Different Penetration Degrees

Decide on 4 mm as the blade width. The fragmented rock volumes of the toothed hob and the flat-top hob are displayed in Table 3 for penetration depths of 5 mm, 7 mm, 9 mm, 11 mm, and 13 mm, respectively.

Table 3. Comparison of rock fragmentation volume between two different types of rolling cutters with different blade widths

penetration (mm)	5	7	9	11	13
Rock mass fragmentation volume of flat-top hob (mm^3)	17670	25910	29910	33340	39330
Rock fragmentation volume of toothed rolling cutters (mm^3)	18860	28860	32410	43410	54650

With increased penetration, the total amount of rock fragmentation for both toothed rolling cutters and flat-top rolling cutters grows continually, and the total rock fragmentation differential between the two increases progressively. The flat-top hob's blade makes greater contact with the rock mass at higher penetration rates. The rock is stronger at this point because it is roughly under triaxial compression. Because only rolling and vertical forces are used by the flat-top hob, it is difficult to harm the rock mass. The rock mass finds it challenging to create a three-dimensional compression condition because to the relatively tiny contact area between the teeth of the toothed hob and the rock mass. As a result, with higher penetration rates, the toothed hob's overall rock fragmentation is greater.

Figure 3 illustrates how the load changes over time at penetration points of 5 mm, 9 mm, and 13 mm for the disc cutter. The hob's vertical force rises linearly with increasing penetration. The rolling and lateral forces of the disc cutter are increased as a result of the increased penetration of the disc cutter, which also expands the contact area between it and the rock mass. The hob's vertical force increase is noticeably larger than its lateral and rolling force increases, suggesting that as penetration rises, the hob blade and cutter body wear more quickly and have a stronger ability to shatter rock. Simultaneously, the inlaid hob exhibits a lower load under varying penetrations in comparison to the flat-top hob. Additionally, the inlaid hob has a greater overall quantity of rock mass crushing, suggesting that it has a more robust rock breaking capability.

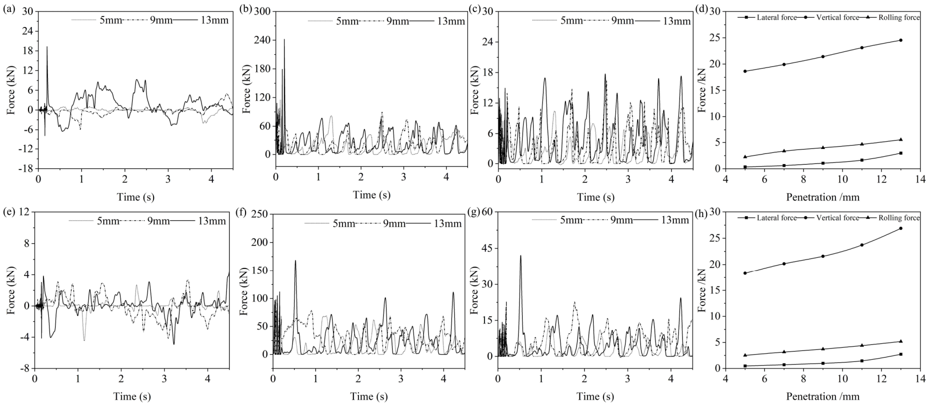

Fig. 3. The (a) lateral force, (b) vertical force, (c) rolling force, and (d) unit time load experienced by flat-top rolling cutters with different penetration, as well as the (e) lateral force, (f) vertical force, (g) rolling force, and (h) unit time load experienced by toothed rolling cutters

4 Conclusion

This paper examines the force characteristics and rock-breaking performance of the cutting edge under various rolling cutter penetration degrees and blade widths by computationally simulating the rock-breaking process of toothed and flat-top rolling cutters. The findings indicate that while increasing the width and penetration of the blade can enhance the hob's ability to break through rocks, doing so would result in increased wear on the rolling cutter. In comparison to a flat-top hob, a toothed hob performs better at breaking rock when the blade width is modest. It also experiences less wear and more rock fragmentation as hob penetration increases. The rock-breaking performance of toothed rolling cutters and flat-top rolling cutters is comparable, and when the blade width is big, the rock-breaking method progressively switches from blade cutting to blade cutting.

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