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ORIGINAL ARTICLE

Fragmentation Energy-Saving Theory of Full Face Rock Tunnel Boring Machine Disc Cutters

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Abstract Attempts to minimize energy consumption of a tunnel boring machine disc cutter during the process of fragmentation have largely focused on optimizing disc-cutter spacing, as determined by the minimum specific energy required for fragmentation; however, indentation tests showed that rock deforms plastically beneath the cutters. Equations for thrust were developed for both the traditional, popularly employed disc cutter and anew design based on three-dimensional theory. The respective energy consumption for penetration, rolling, and side-slip fragmentations were obtained. A change in disc-cutter fragmentation angles resulted in a change in the nature of the interaction between the cutter and rock, which lowered the specific energy of fragmentation. During actual field excavations to the same penetration length, the combined energy consumption for fragmentation using the newly designed cutters was 15% lower than that when using the traditional design. This paper presents a theory for energy saving in tunnel boring machines. Investigation results showed that the disc cutters designed using this theory were more durable than traditional designs, and effectively lowered the energy consumption.

Keywords Newly design · Disc cutter · Fragmentation · Specific energy · Energy consumption

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1 Introduction

A full face rock tunnel boring machine (TBM) is a large underground device for full-scale boring of rock. The cutting of rock requires considerable power (usually up to several thousand kW) and involves massive energy consumption. For example [1], excavation in certain geological strata with either un- or underdeveloped surrounding rocks consumes as much as 3000 kW/h per meter in electrical energy. Researchers around the world have therefore focused on approaches to reduce energy consumption of TBM.

As far back as 1965, Teale [2] proposed the concept of specific energy, defined as the amount of energy required to cut through a unit volume of rock, and thereby introduced the start of a new era in terms of energy-saving designs for TBM. The distinctive feature of this design was the concept of an optimal cutter spacing, which was utilized to determine the position of the disc cutters (the difference between the radii of adjacent disc cutters), i.e., the cutter spacing was determined by the minimum specific energy requirement. In 1978, by using a TBM indentation test, Wang, et al [3] found that an optimal cutter spacing existed for the layout of disc cutters. In 1985, Mao, et al [4] also discovered the existence of an optimal cutter spacing by using a disc-cutter rolling test. In 2007, Gertsch, et al [5] used linear rolling test, determined the optimal spacing of disc cutters used in hard rocks, such as Colorado Red Granite, for which the optimal spacing was 76 mm. Acaroglu, et al [6] developed a fuzzy logic model to predict specific energy requirements for TBM performance. In

2012, Moon, et al [7], through simulations and results obtained in real linear cutting machine (LCM) tests, revealed that the effective rock-cutting condition corresponding to the minimum specific energy could be estimated by an optimized ratio of disc spacing, *s*, to penetration depth, *p* (the *s*/*p* ratio), which, in turn, is linearly proportional to the square of the material brittleness, B^2, and cutter tip width, *t* (i.e., $s/p = cB^2t$, where *c* is a coefficient). In 2013, Cho, et al [8] studied the minimum specific energy required during TBM excavation in a Korean granitic rock using LCM testing and photogrammetric measurement and provided a three-dimensional (3D) digital comparison. In 2015, simulation by Hadi, et al [9] revealed that eroded disc cutters increased the specific energy requirement. Simulations by Mohammad [10] showed that the specific energy requirement of a double disc was less than that of a single disc and that the optimum *s*/*p* ratio was about 10. These studies all focused on constant cross-section (CCS)-type disc cutters and those used earlier. At present, the energy saving method is mainly focus on the traditional cutters [11], and no researches can be found from the public information about designing a new cutter to reduce the energy consumption of TBM. The large energy consumption by use of traditional cutter in the excavation process enhanced the vibration of the cutterhead, increased the disturbance variable in the control of the cutter head system, and influenced the stability of the cutterhead [12].

In 2012, the 3D fragmentation theory of disc cutters was developed [13]. The following year, it was reported that disc cutters designed according to this theory had an apparent enhancement in their lifetime [14] and the specific energy required for fragmentation was lower [15, 16]. Alteration of the angles of the disc cutters during fragmentation was found to be capable of reducing the force required for fragmentation [17].

This work presents fragmentation models of traditional (CCS-type) and newly designed (according to 3D fragmentation theory) disc cutters based on the above research and with consideration of the effects of alternating cutter edge angles. Coupled with a field study, research has been carried out concerning the energy consumption of penetration, rolling, and side-sliding fragmentations. Related field data revealed that the amount of energy required by the newlydesigned disc cutters was 14.8% less than that of traditional cutters.

2 Analysis of Disc-Cutter Fragmentation

Fragmentation by disc cutters involves the process of a resultant forceacting between a disc cutter and its cutting object—the rock, and includes extrusion, stretching, and shearing forces. The complex mechanism and physical properties of rocks, such as anisotropy, fracture, and brittleness, render it difficult to develop a mechanical model of fragmentation by disc cutters: despite much research, this issue remains incompletely resolved.

In this work, on the basis of the relationship between thrust and penetration of disc cutters (Fig. 1), and considering the powder particles nucleated during rolling tests (Fig. 2), we determined that there are two stages in the process of disc-cutter fragmentation. The first is plastic deformation of the rock, during which the rock under the disc cutters is gradually compacted with the so-called 'nucleated powder particles' thus obtained (Fig. 2). This process corresponds to the segment labelled *OA* in Fig. 1. The second stage referred to as 'leap-frog fragmentation'. During the process of 'nucleation', a rock is stripped from those above it, while compressing those underneath it, to the extent that the rocks around it 'lose balance'. This corresponds to segment *ABC* in Fig. 1. Fragmentation of rocks by disc cutters can be expressed by a leap-frog cutting point, *A* (h_a, F_a), on the rock and its corresponding fragmentation value, $H_{a.}$, related studies of which can be found in Refs. [18] and [19].

What interested us was that even before leap-frog fragmentation occurred, deformation of rocks under the action of the disc cutters possessed some features of plasticity, which are shown in Fig. 2. A mechanical model was developed for the mutual interaction between rocks and disc cutters. Theoretical study of the model demonstrated that modification of the disc-cutter edge angles leads to

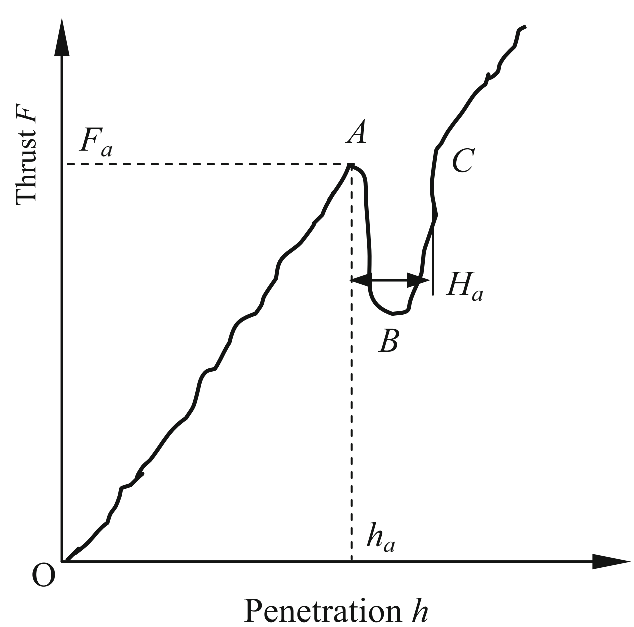

Fig. 1 Disc cutter thrust–penetration curve

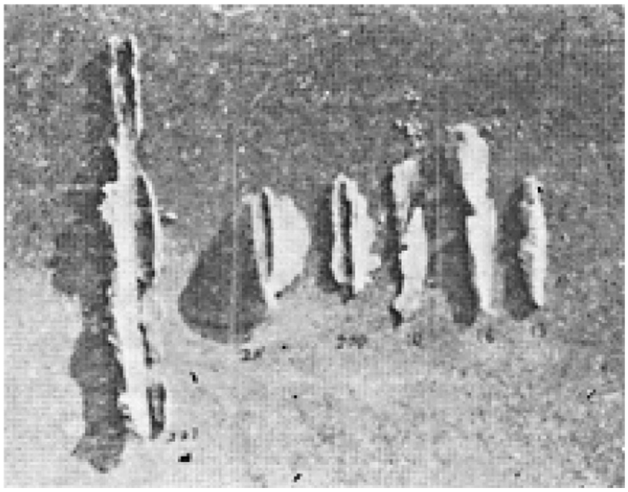

Fig. 2 Nucleated powder particles

effective reduction of the specific energy of fragmentation, as discussed in Refs. [20], [21].

3 Energy Consumption of Traditional and Newly Designed Disc Cutters

3.1 Thrust

The thrust of a disc cutter is the force on the cutter applied by the TBM hydraulic cylinder through the cutter head.

Fig. 3 shows a schematic of a traditional disc cutter and the profile obtained when its penetration depth is h and the rock surface is the cutting plane, with its area denoted as Az. Fig. 4 presents the analogous schematic for the newly designed disc cutter and its resultant profile for a penetration depth of h and rock surface of area Ax.

According to the above analysis, prior to leap-frog fragmentation, rock deformation occurs in accordance with the plasticity law. This lays a foundation for the following calculation. In accordance with Ref. [20], when the penetration of the disc cutter is h, the contact area is in a state of plasticity, which is tantamount to a force acting on plane B–B. For the ith disc (location number) of the newly designed disc cutter, where the force is expressed as q_{xi}, then:

$$q_{xi} = 2k\left(1 + \frac{\pi}{2} - \alpha_i\right). \tag{1}$$

where k is the yield condition. In terms of Mises theory, $k = \sigma_s/\sqrt{3}$; in terms of Tresca theory, $k = \sigma_s/2$, where σ_s is the uniaxial compressive strength of the rock; $\alpha_i = \arctan(r/R_i)$, where r is the radius of a disc cutter and R_i is the radius of the ith disc-cutter locus.

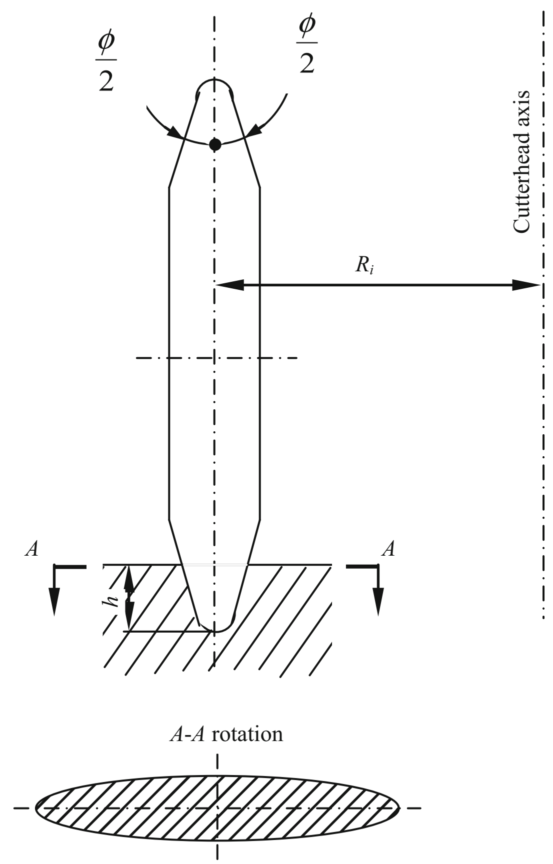

Fig. 3 Traditional cutter ring

Likewise, when penetration of a traditional disc cutter is h, the force q_{zi} acting on the plane B–B is:

$$q_{zi} = 2k\left(1 + \frac{\pi}{2}\right). \tag{2}$$

According to the theory presented in Ref. [22], the thrust F_{zi} on each traditional disc cutter can be expressed as:

$$F_{zi} = q_{zi}A_z = 2k\left(1 + \frac{\pi}{2}\right)A_z. \tag{3}$$

Likewise, the thrust F_{xi} on each newly designed disc cutter is given by:

$$F_{xi} = q_{xi}A_x = 2k\left(1 + \frac{\pi}{2} - \alpha_i\right)A_x. \tag{4}$$

3.2 Energy Consumption

Indentation tests, full-scale linear cutting tests, and analysis of actual cutting by disc cutters showed that the cutting process can be categorized as comprising penetration cutting, full-scale linear cutting, and side-slip cutting. The corresponding energy consumption can be calculated.

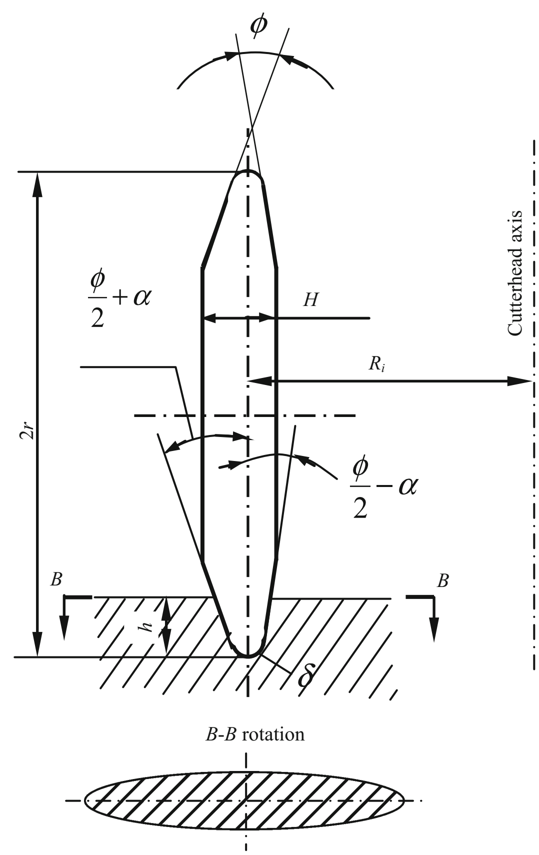

Fig. 4 Newly designed cutter ring

(1) Energy consumption of penetration cutting

Energy consumption of penetration cutting is the work accomplished by the thrust for a certain length of excavation. If the length is L, then W_{zqi}, the energy consumption of traditional disc cutters, is given by:

$$W_{zqi} = F_{zi}L = 2k\left(1 + \frac{\pi}{2}\right)A_z L, \tag{5}$$

while W_{xqi}, the corresponding energy consumption of the newly designed cutters, is:

$$W_{xqi} = F_{xi}L = 2k\left(1 + \frac{\pi}{2} - \alpha_i\right)A_x L. \tag{6}$$

(2) Energy consumption of full-scale linear cutting

Energy consumption of full-scale linear cutting is the energy consumed during the work of the disc cutters. Linear cutting tests revealed that the resistance to disc cutters usually appeared at two-thirds of the penetration depth (shown in Fig. 5); hence, the friction coefficient, η, of the disc cutters is given by:

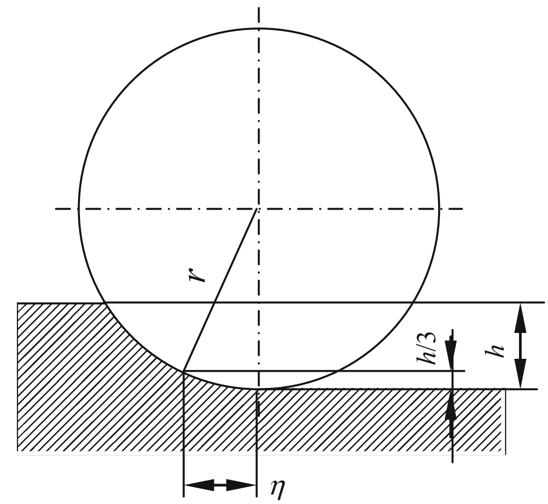

Fig. 5 Calculation of rolling friction coefficient of disc cutter

$$\eta = \frac{\sqrt{6rh - h^2}}{3}. \tag{7}$$

M_{zi}, the frictional torque of traditional disc cutters, is expressed as:

$$M'_{zi} = F_{zi}\eta = 2k\left(1 + \frac{\pi}{2}\right)A_z \frac{\sqrt{6rh - h^2}}{3}. \tag{8}$$

whereas M_{xi}, the corresponding friction torque of the newly designed disc cutters, is given by:

$$M'_{xi} = F_{xi}\eta = 2k\left(1 + \frac{\pi}{2} - \alpha_i\right)A_x \frac{\sqrt{6rh - h^2}}{3}. \tag{9}$$

When the excavation length is L, the revolution number of the cutterhead is L/h; the length of the helix covered is $L/h \times 2\pi R_i$; and the angle passed by a disc cutter is given by:

$$\psi = \frac{L}{h} \times 2\pi R_i \div (2\pi r) \times 2\pi = \frac{2LR_i\pi}{hr}. \tag{10}$$

The energy consumed by linear cutting of traditional disc cutters, W_{zgi}, is:

$$W_{zgi} = M'_{zi}\psi = 4\pi R_i k\left(1 + \frac{\pi}{2}\right)A_z \frac{L\sqrt{6rh - h^2}}{3hr}, \tag{11}$$

while the corresponding value for the newly designed cutter, W_{xgi}, is given by:

$$W_{xgi} = M'_{xi}\psi = 4\pi R_i k\left(1 + \frac{\pi}{2} - \alpha_i\right)A_x \frac{L\sqrt{6rh - h^2}}{3hr}. \tag{12}$$

(3) Energy consumption of side-slip cutting

Side slip is the sideways motion of disc cutters in the direction perpendicular to the plane of the cutter edge. Without revolution of the cutterhead, i.e., without transport motion or penetration of the disc cutters, there would be no side slip; therefore, side slip is the result of both cutterhead revolution and disc-cutter penetration. The energy consumption is that consumed by disc cutters undergoing side slip, as shown in Fig. 6.

In Fig. 6, O_1O_2 is the axis of a disc cutter, O_2O_3 is the axis of the cutterhead, $h$is the penetration, D is the instantaneous disc-cutter maximal penetration point, and C is the instantaneous disc-cutter cutting point. Because it is transport motion (revolution of the cutterhead) that leads to side slip, an analysis of transport motion is presented.

When a disc cutter passes through angle $d\gamma$ (not shown in Fig. 6 for clarity), the corresponding point on the cutterhead also passes through angle $d\gamma$. In accordance with the geometric relationship shown in Fig. 6, the magnitude of the transport displacement of point C, denoted by $d\Lambda_i$, is expressed as:

$$d\Lambda_i = \overline{CF} = \overline{AC}d\gamma = \frac{\overline{O_3D}}{\cos\gamma}d\gamma = \frac{R_i}{\cos\gamma}d\gamma \tag{13}$$

and that of side-slip displacement of point C, represented by $d\Delta$, is given by:

$$d\Delta_i = \overline{GF} = \overline{CF}\sin\gamma = R_i\tan\gamma d\gamma. \tag{14}$$

The length of arc of the locus corresponding to one revolution of a disc cutter is $2\pi r$ and the angle corresponding to the arc between focal radii is $2\pi r/R_i$, so the corresponding side-slip displacement, Δ_i, can be expressed as:

$$\Delta_i = \int_0^{\frac{2\pi r}{R_i}} d\Delta_i = \int_0^{\frac{2\pi r}{R_i}} R_i\tan\gamma d\gamma = -R_i\ln\cos\frac{2\pi r}{R_i}. \tag{15}$$

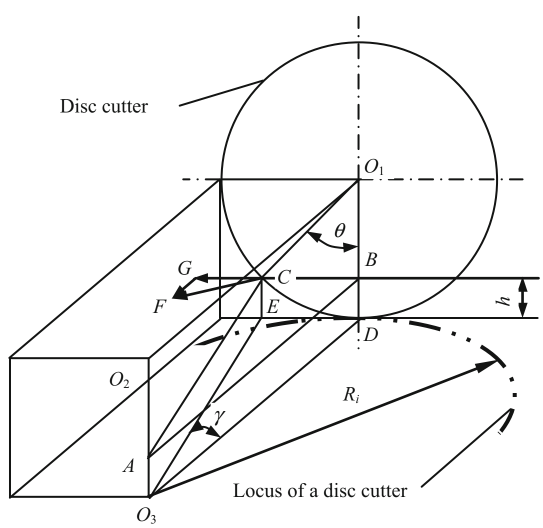

Fig. 6 Actual fragmentation of a disc cutter

When excavation length is L and the revolution number of cutterhead is L/h, then for each revolution of the cutterhead, the revolution number of the disc cutter is $2\pi R_i/2\pi r = R_i/r$. The corresponding disc-cutter side slip is:

$$\Delta_{iL} = \frac{L}{h} \times \frac{R_i}{r}\Delta_i = -\frac{R_i^2 L}{rh}\ln\cos\frac{2\pi r}{R_i}. \tag{16}$$

The side-slip energy consumption of a traditional disc cutter, W_{zhi}, is therefore given by:

$$W_{zhi} = F_{zi}f\Delta_{iL} = -\frac{2kR_i^2 L}{rh}\left(1+\frac{\pi}{2}\right)A_z f\ln\cos\frac{2\pi r}{R_i}, \tag{17}$$

while that of a newly designed disc cutter, W_{xhi}, is given by:

$$W_{xhi} = F_{xi}f\Delta_{iL} = -\frac{2kR_i^2 L}{rh}\left(1+\frac{\pi}{2}-\alpha_i\right)A_x f\ln\cos\frac{2\pi r}{R_i}. \tag{18}$$

4 Energy-Saving Analysis of Newly Designed Disc Cutter Fragmentation

4.1 Basic Theory

Suppose there are n disc cutters on the cutterhead and the excavation length is L, then the thrust energy, W_z, the rolling energy, W_{zg}, and the side-slip energy, W_{zh}, consumed are, respectively:

$$W_z = \sum_{i=1}^{n} W_{zi} = \sum_{i=1}^{n}\left[2k\left(1+\frac{\pi}{2}\right)A_z L\right]; \tag{19}$$

$$W_{zg} = \sum_{i=1}^{n} W_{zgi} = \sum_{i=1}^{n}\left[4\pi R_i k\left(1+\frac{\pi}{2}\right)A_z\frac{L\sqrt{6rh-h^2}}{3hr}\right]; \tag{20}$$

$$W_{zh} = \sum_{i=1}^{n} W_{zhi} = \sum_{i=1}^{n}\left[-\frac{2kR_i^2 L}{rh}\left(1+\frac{\pi}{2}\right)A_z f\ln\cos\frac{2\pi r}{R_i}\right]. \tag{21}$$

The corresponding values for n newly designed disc cutters are:

$$W_x = \sum_{i=1}^{n} W_{xi} = \sum_{i=i}^{n}\left[2k\left(1+\frac{\pi}{2}-\alpha_i\right)A_x L\right]; \tag{22}$$

$$W_{xg} = \sum_{i=1}^{n} W_{xgi} = \sum_{i=1}^{n}\left[4\pi R_i k\left(1+\frac{\pi}{2}-\alpha_i\right)A_x\frac{L\sqrt{6rh-h^2}}{3hr}\right]; \tag{23}$$

$$W_{xh} = \sum_{i=1}^{n} W_{xhi} = \sum_{i=1}^{n} \left[-\frac{2kR_i^2 L}{rh} \left(1 + \frac{\pi}{2} - \alpha_i\right) A_x f \ln \cos \frac{2\pi r}{R_i} \right]. \quad (24)$$

Comparing a TBM with n traditional disc cutters with one with n newly designed disc cutters over the same excavation length L, the thrust energy consumption drops by λ, expressed as:

$$\lambda = \frac{W_z - W_x}{W_z} \times 100\% = \frac{\sum_{i=1}^{n} \alpha_i}{\sum_{i=1}^{n} \left(1 + \frac{\pi}{2}\right)} \times 100\%. \quad (25)$$

The rolling energy consumed by a TBM with n newly designed disc cutters, compared with one using n traditional disc cutters over the same excavation length L drops by:

$$\varepsilon = \frac{W_{zg} - W_{xg}}{W_{zg}} \times 100\% = \frac{\sum_{i=1}^{n} R_i \alpha_i}{\sum_{i=1}^{n} R_i \left(1 + \frac{\pi}{2}\right)} \times 100\%. \quad (26)$$

Likewise, the side-slip energy consumed by a TBM with n newly designed disc cutters, compared with that consumed using the same number of traditional disc cutters over the same excavation length L is reduced by:

$$\beta = \frac{W_{zh} - W_{xh}}{W_{zh}} \times 100\% = \frac{\sum_{i=1}^{n} \left(R_i^2 \alpha_i \ln \cos \frac{2\pi r}{R_i}\right)}{\sum_{i=1}^{n} \left[R_i^2 \left(1 + \frac{\pi}{2}\right) \ln \cos \frac{2\pi r}{R_i}\right]} \times 100\%. \quad (27)$$

4.2 Case Study and Verification

This theory substantiates the theoretical results of Ref. [20], in which the specific fragmentation energy of newly designed disc cutters, compared with that of traditional cutters, is reported to drop by:

$$\zeta = \frac{1}{n} \sum_{i=1}^{n} \frac{2\alpha_i}{2 + \pi} \times 100\%. \quad (28)$$

In accordance with Ref. [20], the theoretical basis of Eq. (28) is that when a disc cutter penetrates a rock, the area around it is converted to a state of plasticity. During this process, the disc cutter and rock interact with each other through compression and partially through rolling, i.e., the process involves energy consumption by thrust and partially by rolling:

$$\lambda + \varepsilon > \zeta. \quad (29)$$

The parameters adopted for the disc cutters in this case study, such as locus and disc-cutter radii, are given in Ref. [22]. Substituting the corresponding parameters into Eqs. (25)–(28), we respectively obtained: $\lambda = 6.808\%$, $\varepsilon = 3.477\%$, $\beta = 4.516\%$, $\zeta = 8.372\%$. The fact that these results satisfy Eq. (29) demonstrates that the theory presented is essentially correct. It can also be concluded that energy savings by employing newly designed disc cutters could reach 6.808% + 3.477% + 4.516% = 14.801%.

5 Conclusions

Based on experimental data for fragmentation by disc cutters and analysis of the fragmentation forces of single traditional and newly designed disc cutters, the following conclusions are drawn:

1) Equations are proposed for the fragmentation energy consumption of single traditional and newly designed disc cutters;
2) Equations are developed for fragmentation energy consumption of the traditional and newly designed disc cutters positioned on the cutter head;
3) Comparative study showed that a TBM equipped with the newly designed disc cutters used less energy than one with traditional cutters; i.e., under the same fragmentation conditions and for the same penetration, the energy consumption of the newly designed disc cutters was about 15% lower than that of the traditional cutters.

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