The Effect of Disc Cutter Parameters on Rock Fragmentation in Tunnel Boring Machines

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Abstract -- In order to study the influence of rock fragmentation by disc cutter in the condition of different rock temperatures, on the basis of particle flow, the cutter's particle flow numerical model is established from the microscopic view. The influence of changing the cutter's structure parameters on rock-breaking mechanism at different rock temperatures is numerically simulated and analyzed, thus explaining the rock-breaking mechanism of changing structural parameters from micro view for disc cutter. The results show that: (1) Increasing rock temperature can greatly reduce the rock mechanical properties such as hardness, strength, rapid extension of micro cracks, crack number increase, all of which resulting in the rock-breaking load and specific energy consumption to be reduced and the rock-breaking efficiency be improved for disc cutter; (2) The higher the blade width, the larger the rock-breaking load and the energy consumption, the more the number of acoustic emission events, all of which reducing the efficiency of rock-breaking; (3) The parameters changing of blade angle mainly influence the number of crack and acoustic emission events, while having little effect on rock-breaking load and specific energy consumption.

Keywords - TBM; Disc cutter; Rock temperature; Rock fragmentation; Numerical simulation

I. INTRODUCTION

The Tunnel Boring Machine (TBM for short), which operates parallel continuously along with many constructing processes such as tunneling, supporting, de-slagging etc., is an important tunnel construction engineering equipment integrated of mechanism, electric, hydraulic, light, gas and other systematic system. It has many advantages: high tunneling speed, protecting environment and high benefits and so on. TBM can permit the construction of deep buried long tunnel complex topography that is difficult to achieve by the traditional drilling and blasting method. So the using of TBM is growing rapidly in the China Water Conservancy and hydro-power, communications, mining and municipal tunnel engineering applications. [1-3] Disc cutter is the main tool for TBM to break rock, which rock-breaking efficiency directly affects the tunnel excavation progress. Cutter ring is the direct contacting component for TBM to rock and bears their interaction load. When cutter ring in use, the thrust force by cutter head acts on rock through blade angle of cutter ring, and then rock behave failure and produce massive rock slags. Furthermore, disc cutter intrude into rock, which producing failure zone due to the shear and extrusion load from disc cutter, and ultimately achieve the effect of broken rock. [4-7] At present, there are little domestic and foreign researches on the effects of structural parameters on rock fragmentation at different rock temperatures. To reveal the influence of rock temperature on the disc cutter's rock fragmentation, is the key to ensure the efficient, safe and reliable tunneling for TBM. Different rock temperatures will greatly affect the rock-breaking performance for TBM. The disc cutter design separately from the geological factors of rock temperature will be good job in the specific underground. But in other geological environment excavation has shown poor geological adaptability. The domestic and foreign scholars have conducted some researches on the rock breaking mechanism of disc cutter in theory, simulation and experiment, but did not realize the comprehensive and unified. [8,9] Therefore, we attempts to research the influence of disc cutter structure parameters on rock fragmentation of disc cutter under the conditions of different rock temperatures. Furthermore, we also accomplish the numerical simulation analysis to provide a theoretical basis for the study of rock-breaking mechanism of TBM disc cutter. At the same time, this research has certain theoretical value and engineering significance to improve rock-breaking efficiency, enhance geology adaptability and use life, achieve tunnel with high efficiency and low energy consumption and low loss.

II. NUMERICAL MODEL OF ROCK FRAGMENTATION BY TBM CUTTER

At present, the 17# disc cutter is mainly used in domestic on TBM cutter head and 19# disc cutter is seldom used, 12# disc cutter has been eliminated. Because of wide application of flat blade cutter ring in engineering, we take the 17# disc cutter, which is the most widely used to approximate soft and medium hard underground, as the research object in this paper. At present, there are mainly two kinds of cutter structure: one cutter ring is a symmetrical structure; the other cutter ring is non symmetrical structure in purpose of reducing the abrasion. In this paper, we take the first kind as research object such as Figure.1, which is mainly composed of cutter shaft, sealing ring, upper cover, a lower cover, cutter ring, bearing, cutter hub, snap ring, locking plate and screws etc. The main geometric parameters are: the blade

width of top cutter B is 10mm, transition radius r is 4mm, blade angle is 20 degrees. [10]

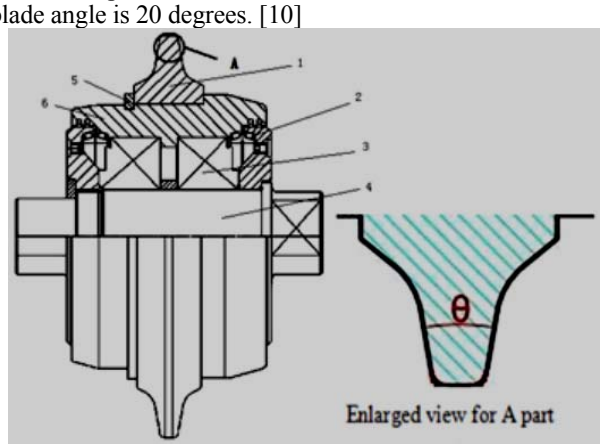

Figure.1. TBM Disc Cutter

1-cutter ring; 2-sealing ring; 3-bearing; 4-cutter shaft; 5-snap ring; 6-cutter hub

Furthermore, we select the marble from hard rock stratum as the research object, the macro mechanical parameters of rock specimen are shown in table 1. The meso mechanical parameters of rock specimen need to be repeat calibrated through numerical experiments simulating uniaxial compression and splitting Brazil to match its macro mechanical parameters. Assuming that the maximum and minimum radius ratio is 1.66 for the numerical model of rock specimen, the minimum radius of particles is 0.8 mm and the density ρ is 3375kg·m-3 . For that the rock specimen porosity exists, so the density of the particle density is greater than the macro rock specimen. [11]We select the contact bond model to simulate the contact between particles. The size of numerical rock specimen for uniaxial compression test is 100mm*50 mm. The diameter of numerical rock specimen for Brazil splitting test is 50mm. The microscopic parameters of rock specimens in PFC2D after calibrating is shown in table 2.

TABLE I THE MACRO MECHANICAL PARAMETERS OF ROCK SPECIMEN

Density /kg.m^{-3}	Elastic modulus /GPa	Compressi-on strength /MPa	Poisson ratio	Cohesiv e force /MPa	internal friction angle /°
2700	40	100	0.18	25	40

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TABLE II THE MESO MECHANICAL PARAMETERS OF ROCK SPECIMEN

When breaking rock, the contact surface between disc cutter to rock present "trench" shape, while the process of rock breaking mainly occurred on the surface vertical to the cutter's tunneling direction. Therefore, we can take the rock-breaking process as a plane problem. Thus the action of the crack propagation process under the action of disc cutter can still be approximately simulated without considering the tangential rolling rock-breaking effect. Cutter ring is manufactured by material with high surface hardness, which strength and stiffness is very high. Therefore, the cutter ring can be regarded as a rigid body and its contour is presented by a rigid wall. Figure.2 shows the numerical model of rock fragmentation by TBM cutter. The number of particles for rock specimen contains is 22097. Rock specimen is introduced into a square slot fixed by three wall surrounding. There is no friction between rock specimen and wall. The disc cutter is simplified as a folding wall. The stiffness of the wall is simplified far greater than that for particle to avoid deformation of the wall (disc cutter). By changing the temperature of rock, blade width and blade angle, the crack propagation and rules of stress and strain can be observed under different conditions.

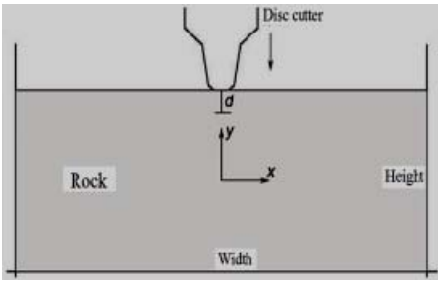

Figure.2. Numerical model of rock fragmentation by TBM cutter

In particle flow code, we take the microscopic model of thermal storage relating particles and heat pipe relating to contact key to simulate the macro temperature field, with heat transferred by the activated thermal storage in heat pipe. When there is overlapping or contact key between two particles' contact in rock specimen, heat pipe between thermal storage is activated. On the other hand, when there is no overlapping or contact key between two particles' contact in rock specimen in the loading process, the number of activated heat pipe will be affected, and then the macro thermal properties of materials also be changed. [12] The main structure parameters of disc cutter ring are: blade width B and blade angle θ, which affect more on the rock-breaking load and efficiency and so forth. The breaking process of rock, concrete and other materials can be seen as fracture of key contact between the particles. The rock specimen size is 300 * 160mm2, which randomly generated after giving meso parameters in Table 2. The blade width are respectively valued 10, 14, 18, 22, 26 mm, blade angle are respectively valued 5, 10, 20, 30, 40 degree of different structure parameters. According to the assigned parameter values to numerical simulated.

III. NUMERICAL SIMULATION ANALYSIS

A. Influence of Blade Width on Rock Fragmentation under Different Rock Temperatures

Figure.3 shows the influence of disc cutter's blade width on rock-breaking load under different rock temperatures. The results show that: with the disc cutter's blade width

increases, the rock-breaking load shows the corresponding increase gradually. Thus showing that blade width is a important factor affecting the rock- breaking load of TBM disc cutter. Increasing of blade width will increase the contact area of disc cutter to rock. When disc cutter intrude into rock, the rock-breaking load natural increasing. After comparing of the rock-breaking load under different temperatures of disc cutter, we can see that with increasing temperature, the rock-breaking load decreasing.

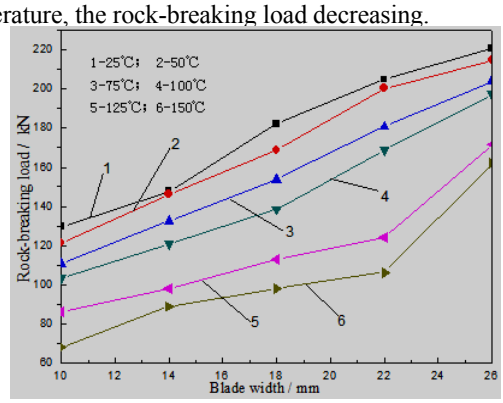

Figure.3. Influence of blade width on rock-breaking load under different rock temperatures

Figure.4 shows the influence of blade width on the number of acoustic emission events under different rock temperatures. It can be seen that as the blade width increases, the number of acoustic emission events increases. With the increase of rock temperature, due to changes in rock stress and blade width increases, the cutting force from the rock to disc cutter increases. So more cracks appear in the rock, so do the corresponding AE number increases. With the increase of rock temperature, the increase of the number of acoustic emission events increased greatly.

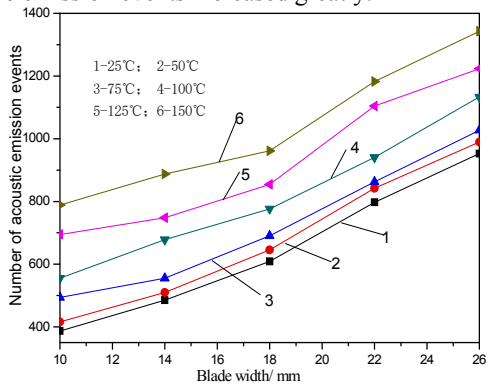

Figure.4. Influence of blade width on the number of acoustic emission events under different rock temperatures

Figure.5 shows the influence of blade width on rock-breaking specific energy consumption under different rock temperatures. It can be seen that at the same rock temperature, the tendency of rock-breaking specific energy consumption is ascend in first and descend at last with the blade width increasing. This is because when the blade width is small, the contact area of disc cutter to rock is small, and so the rock-breaking load is relatively small. Therefore, the corresponding rock-breaking power and crushing volume is relatively small. With the blade width increase, it enlarges the contact area of cutter blade to rock. The rock-breaking load, breaking power and breaking volume corresponding increase gradually. But the rock-breaking volume increases to a greater extent than the breaking power and then the specific energy consumption decreases. When the blade width increases to a certain degree, the amplitude of breaking power increases more than that of rock-breaking volume, so the rock-breaking specific energy consumption gradually increases. With the increase of rock temperature, the rock-breaking specific energy consumption reduces, showing that the higher the rock temperature is, the higher the rock-breaking efficiency of cutters is. When using disc cutter with smaller blade width, less intrusive energy consumption is needed. But the wear resistance is poor and is not conducive to the long time stability of rock breaking. When using disc cutter with larger blade width, the wear resistance is good and rock-breaking load is needed more at the same penetration depth. So the corresponding energy consumption is larger. The blade width is usually set about 20 mm to achieve a balance between the wear resistance, the efficiency of rock-breaking and rock-breaking load.

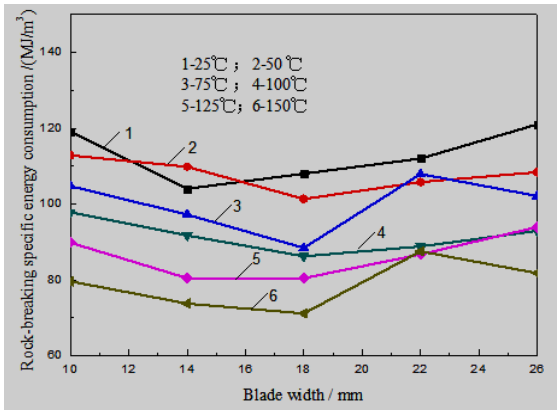

Figure.5. Influence of blade width on rock-breaking specific energy consumption under different rock temperatures

B. Influence of Blade Angle on Rock Fragmentation under Different Rock Temperatures

Figure.6 shows the influence of disc cutter's blade angle on rock-breaking load under different rock temperatures. The results show that: under the same rock temperature, the rock-breaking load of disc cutter gradually increased with the increase of the blade angle, but the increase rate is very small. This indicating there is little influence of blade angle on rock-breaking load for TBM disc cutter.

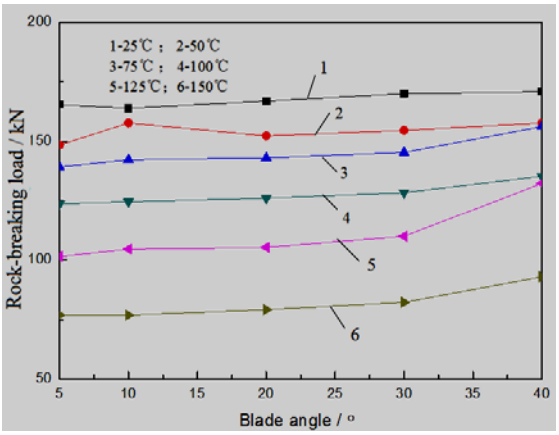

Figure.6. Influence of blade angle on rock-breaking load under different rock temperatures

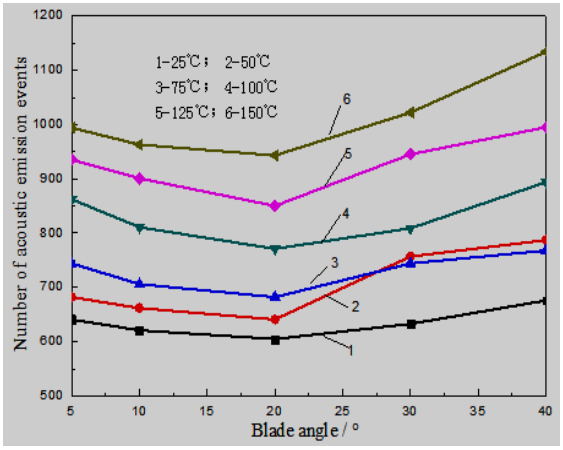

Figure.7. Influence of blade angle on the number of acoustic emission events under different rock temperatures

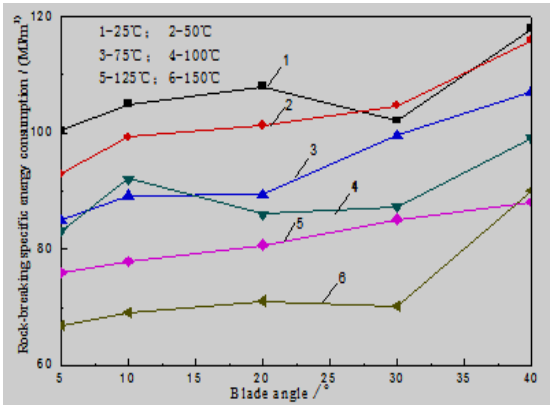

Figure.8. Influence of blade angle on rock-breaking specific energy consumption under different rock temperatures

Figure.7 shows the influence of blade width on the number of acoustic emission events under different rock temperatures. It can be seen that as the blade angle increases, the occurrence of rock AE number decreases to a certain value to reach the minimum, and then increased. That illustrates blade angle is an influence factor of rock acoustic emission events. Make full use of the small cutter blade angle shear rock lateral crack on both sides of the blade easy to form a larger rock, the number of acoustic emission events become larger and the blade angle increases. The shear effect decreases, the corresponding acoustic emission event number decreases. Blade angle increases to a certain value, the number of acoustic emission reaches the minimum value. With the blade angle increases again, the compressing action of disc cutter on both sides rocks enhanced and inhibit the shear cracks in the side, so the number of acoustic emission events increases.

Figure.8 shows the influence of blade angle on rock-breaking specific energy consumption under different rock temperatures. It can be seen that with the increase of the blade angle, the specific rock-breaking energy consumption gradually increased. But the increasing scope

IV. CONCLUSIONS

(a) By using the PFC rock-breaking model of disc cutter, we studied the influence of structure parameters on rock-breaking characteristics under different rock temperatures. Thus explaining the different structure parameters influence of the rock fragmentation for disc cutter under the geological conditions of different rock temperatures from the microscopic view. By using the two-dimensional particle flow code on the cutter rock-breaking process simplification and simulation, it can be obtained with the actual cutter rock breaking the same effect. In some cases it can be completed in the actual condition of the research work, meanwhile saving the cost of scientific research.

(b)The simulation studies that under different conditions of disc cutter shows: rock temperatures, blade width and blade angle all have certain influences on disc cutter’ s rock-breaking efficiency: the higher the rock temperature, the lower the rock-breaking load and rock-breaking energy consumption; the greater the blade width, the larger the rock-breaking load, the number of acoustic emission events and the rock-breaking specific energy consumption; while blade angle mainly affects the number of acoustic emission events and crack control for TBM disc cutter, and has little effects on rock-breaking load and rock-breaking specific energy consumption.

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