Study on Forming Technology of TBM Disc Cutter Ring

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Abstract. The tunnels and underground projects bring an unprecedented development of hard rock tunneling technology. The forming process and material properties of the 20 inch disc cutter ring have been studied by the finite element simulation and test methods. The effects of blank size, blank heating temperature, mold preheating temperature and friction coefficient on the forming load, minimum surface temperature and blank deformation uniformity of 20 inch cutter ring were analyzed. The results show the optimum combination of the forming process of the 20 inch disc cutter ring is when the blank height is 90 mm, the blank heating temperature is 1200 °C, the preheating temperature is 280 °C, and the friction coefficient is 0.2.

Compression test and hardness test were carried out on the edge material of the cutter ring. The test results show that when the temperature exceeds 600 °C, the hardness and compressive strength of the cutter ring material will drop sharply. Therefore, the TBM should be properly cooled during construction. The research results in this paper can provide a basis for the optimization of TBM disc cutter ring processing technology and engineering applications.

1. Introduction

Tunnels and underground projects have been developed rapidly in recent years. The Full Face Hard Rock Tunnel Boring Machine (TBM) is more and more favored by the construction unit because of its remarkable advantages such as safety and efficiency and reliable construction quality [1, 2]. The cutter ring is a key part of the TBM rock breaking. It will withstand loads such as extrusion, torsion, impact and vibration during work, and the working conditions are very bad.[3]. The loss of the cutter ring is an important factor that restricts the efficiency and economy of TBM construction. During the construction of TBM, the cost of tool consumption accounts for about one-third of the total construction cost. The repair and replacement of the cutter ring and the maintenance of the cutter head...
can take more than 30% of the total construction period [4, 5]. This paper combines the size and material properties of the cutter ring to optimize the forming process of the cutter ring, thereby improving the construction efficiency of the TBM.

2. Simulation analysis of cutter ring forming process
In this paper, through the use of DEFORM software and orthogonal test method, the 20 inch cutter ring forming process is studied to determine the optimal forming process of 20 inch cutter ring, and the experimental verification was carried out.

2.1. Influencing factors and levels of cutter ring forming
The change of the blank height will change the degree of deformation of the material in the forming process of the cutter ring. The heating temperature of the blank will affect the deformation resistance of the material. The preheating temperature of the mold has a great influence on the heat exchange between the die and the blank. The amount of friction between the dies can have an important effect on the flow state of the blank material. Therefore, this paper selects the blank height (factor A), the blank heating temperature (factor B), the mold preheating temperature (factor C) and the friction coefficient (factor D) as the influencing factors of the 20 inch cutter ring forming process. Each factor takes three levels.

The ring-shaped H13 steel is used to form blank for 20 inch cutter ring forming. Compared with the solid steel ingot as the processing raw material, the use of the ring material can save more than 40% of the raw materials. Equation (1) is the formula for calculating the blank volume, in the formula: \( V \) is blank volume, \( D \) is blank outer diameter, \( d \) is blank inner diameter, \( H \) is blank height.

\[
V = \frac{\pi}{4}(D^2 - d^2)H
\]

| Factor level | Factor A (mm) | Factor B (♀) | Factor C (℃) | Factor D |
|--------------|--------------|--------------|--------------|---------|
| 1            | 80           | 1060         | 180          | 0.2     |
| 2            | 85           | 1130         | 230          | 0.3     |
| 3            | 90           | 1200         | 280          | 0.4     |

2.2. Influencing factors and levels of cutter ring forming
In this paper, the minimum final forging temperature \( T \), the blank deformation uniformity \( \delta \) and the forming load \( P \) of the forging surface are selected as the optimization targets of the cutter ring forming. In the three optimization objectives of the cutter ring forming analysis, the minimum final forging temperature of the cutter ring will directly affect the crack during the forming process. So the minimum final forging temperature \( T \) is the first optimization goal. The uniformity of the blank deformation will have a certain impact on the overall mechanical properties of the cutter ring, which will affect the working capacity and service life of the cutter ring, so the blank deformation uniformity \( \delta \) is the second optimization goal. The optimization of the forming load is mainly from the perspective of improving energy efficiency and prolonging the service life of the mold, and has little influence on the performance of the cutter ring, so the forming load \( P \) is the third optimization target.

2.3. Simulation model establishment and pre-processing
The mold is simplified into a rotationally symmetric model, and a quarter model is used for simulation analysis as in Figure 1. The forming mold is simplified to a rigid body regardless of the slight deformation of the mold.

Import the simplified model into the DEFORM software and select the tetrahedral element to mesh the model. Define the upper mold as the main mold (PDie), the direction of motion is -Y direction, the speed is 70mm/s. The heat exchange coefficient value between the mold and the blank was 11
N/s/mm°C. The number of simulation steps is 120 steps, the step size is 0.5 mm, and the simulation termination condition is the upper and lower mold clamping.

![Simulation analysis model](image)

**Figure 1.** Simulation analysis model (a) Upper mold, (b) Blank, (c) Lower mold.

### 2.4. Simulation result analysis

According to the L9 ($3^4$) orthogonal table arrangement test, nine sets of simulation analysis were carried out on the cutter ring forming process. In the nine sets of tests, the cutter ring can reach the ideal forming state, and the range analysis is performed for the final forging temperature, deformation uniformity and forming load change during the forming process of the cutter ring. The minimum final forging temperature, the uniformity of blank deformation, the forming load of the cutter ring with the level of each factor and the distribution of the range are shown in Figure 2 to Figure 7.

![Minimum final forging temperature](image)

**Figure 2.** The minimum final forging temperature varies with each factor level

![Forging temperature distribution](image)

**Figure 3.** The minimum final forging temperature distribution of the cutter ring

![Deformation uniformity](image)

**Figure 4.** The deformation uniformity of the blank varies with the level of the factor

![Blank deformation uniformity](image)

**Figure 5.** The range distribution of blank deformation uniformity

![Forging load](image)

**Figure 6.** Cutter ring forming load varies with factor level

![Forming load range](image)

**Figure 7.** The range distribution of cutter ring forming load

It can be seen from the graphs of Figure 2 to Figure 7. that the optimum forming parameter level of the 20 inch cutter ring is $A_3B_3C_3D_1$, that is, the blank height is 90 mm, the blank heating temperature is 1200 °C, the mold preheating temperature is 280 °C, and the friction coefficient is 0.2. So a good performance cutter ring can be obtained under the combination of this parameter.
3. Cutter ring trial

3.1. Cutter ring test piece forming

In order to ensure the forming quality of the cutter ring and the performance of the forging-shaped equipment, the J53-8000 screw press was used, and the load of the two-stroke was applied to complete the 20 inch cutter ring forging. The first strike is the main deformation process of the cutter blank; the second strike is the formation of the flash and the performance improvement of the forging.

The curve of 20 inch cutter ring forming pressure with the upper mold stroke is shown in Figure 8. The curve turning point in the figure is the position where the flash begins to appear. The first hit load is 40 MN and the second hit load is 75 MN. The 20 inch TBM cutter test piece was tested according to the above process, as shown in Figure 9. As can be seen from the figure, the cutter ring is in good shape.

![Figure 8. Curve of 20 inch cutter ring forming pressure with the upper mold stroke.](image1)

![Figure 9. 20 inch cutter ring test piece.](image2)

3.2. Cutter ring test piece heat treatment

In order to meet the practical application requirements of the project, a reasonable heat treatment of the TBM cutter ring is required. The combination of quenching and tempering can effectively improve the surface hardness of H13 die steel, promote the uniform distribution of tiny carbides and strengthen the microstructure of H13 steel. Alloy elements such as Si in H13 steel have obvious secondary hardening effect and strong tempering resistance. Multiple tempering helps to improve the strength, hardness and toughness of H13 steel [6,7]. For the TBM cutter ring test, this paper uses high temperature quenching and two tempering processes for heat treatment.

4. Cutter ring material performance test

The edge of cutter ring is the part that contacts rock directly in the process of rock breaking by TBM, and the wear condition is the most serious. At the same time, because of the contact and friction with rock, the high temperature area will appear on the edge surface of the cutter ring. In order to verify the performance of the TBM cutter ring, the compression test and hardness test are performed on the edge surface of the TBM cutter ring from 25 °C to 700 °C.

4.1. Compression test

The edge material of TBM cutter ring was processed into a compressed sample of 5 mm × 5 mm × 10 mm as shown in Figure 10. The DDL type electronic universal testing machine was used to carry out the compression test on the sample, and the curve of the comprehensive strength of the edge material with temperature was measured as shown in Figure 11.
The strength limit of ordinary H13 die steel at 25 °C is about 1500 MPa. According to the forming process and heat treatment, the 25 °C comprehensive strength of the cutter ring material can reach 2700 MPa or more, and the normal temperature comprehensive strength of the cutter ring material is significantly improved.

It can be seen from Figure 11, that as the temperature increases, the comprehensive strength of the edge material decreases. When the temperature exceeds 700 °C, the comprehensive strength of the material of the edge portion is less than 500 MPa. TBM construction relies on the cutter ring to crush the rock to complete the excavation process. If the TBM cutter ring performs continuous rock breaking work under high temperature environment, it is easy to cause serious wear and even crushing.

4.2. Hardness Testing
The edge material of the TBM cutter ring specimen was selected, and the material was processed into a 10 mm×10 mm×3 mm hardness test specimen according to the size shown in Figure 12. The hardness curve of the edge material measured with Rockwell hardness of HR-150A is shown in table 2. It can be seen from the table that as the temperature increases, the hardness of the edge material gradually decreases. When the temperature reaches 700 °C, the hardness of the edge material is only 33.2HRC. The wear resistance and strength will be greatly reduced, and the cutter ring is not suitable for continuous operation for a long time.

| Temperature(°C) | Room temperature (25) | 100 | 200 | 300 | 400 | 500 | 600 | 700 |
|----------------|-----------------------|-----|-----|-----|-----|-----|-----|-----|
| Hardness (HRC) | 58.9                  | 58.5| 57.3| 56.8| 56.1| 55.5| 51.3| 33.2|

5. Conclusions
(1) The annular blank is used as the processing raw material, which can save more than 40% of raw materials compared with the traditional processing technology of the cutter ring with solid blank as raw material.
(2) The optimal forming process parameters of the 20 inch cutter ring were determined as the blank height of 90mm, the blank heating temperature of 1200 °C, the mold preheating temperature of 280 °C, and the friction coefficient of 0.2. Under this parameter combination, the cutter ring is in good condition without defects.

(3) The hardness and comprehensive strength tests were carried out on the blade edge material at 25 °C~700 °C. The results show that the performance of the cutter ring material is significantly improved at lower temperatures. When the temperature exceeds 600 °C, the material hardness and comprehensive strength began to drop dramatically.

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