

REVIEW

Development and Application of Complete Equipment for High-speed Tunnel Boring and Bolting Machines

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ABSTRACT

With the improvement of coal mining speed and mechanization level in China, traditional tunnel boring methods can no longer meet the actual needs. In order to solve the problems of low efficiency, high labor intensity, slow tunnel boring speed, bad working environment and poor safety in traditional tunnel boring, on the basis of analyzing the development and application of coal roadway tunnel boring equipment at home and abroad, complete equipment for high-speed tunnel boring and bolting machines was developed by using the integrated technology of tunnel boring and bolting. The complete equipment for high-speed tunnel boring and bolting machines has the functions of tunnel boring and bolting synchronization, once-tunneling, negative pressure dust removal, digital guidance, independent cutting feed, digital cutting, safety monitoring and data interaction, which has the advantages of safety in use, reliability and efficiency.

1. Introduction

At present, China is the largest country in the use of coal machinery manufacturing and coal mine equipment. There are more than 130 imported tunnel boring and bolting machines in China. Most of the machines has reached the service life, and it is urgent to update and technically reform.^[1] In the “Guiding Opinions on the 13th Five-Year Equipment Manufacturing Development of the Coal Industry” it has also been clearly proposed to vigorously promote the efficient tunnel boring technology for large-section roadways, high-speed tunnel boring technology and equipment for coal and coal-rock roadways, and integrated technology and assembly for tunnel boring to build an intensive, safe, efficient and

green modern coal industry system. By 2020, the degree coal mining mechanization of will reach 85%, and the degree of tunnel boring mechanization will reach 65%.^[2] Therefore, the development of domestic high-speed tunnel boring and bolting machines is of great significance.

2. Research Status of Bolter Miners at Home and Abroad

2.1 Overseas Research Status

The tunnel boring and bolting machine is an organic combination of continuous miner and jumbolter. In 1990, Austrian Voestalpine AG researched and developed the ABM20 Bolter Miner based on the experience and needs of Australian coal mining. The machine is equipped with

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4 roof jumbolters, 2 side jumbolters and temporary support devices. The main and auxiliary frames can slide relatively to each other with tunnel boring and bolting synchronization and the functions are complete. In 1992, it was modified to the ABM30 Bolter Miner, whose capacity of cutting and mechanism loading has been further increased. In the same year, British Anderson Co. Ltd. developed a prototype of the KBII Bolter Miner. The structural features are roughly equivalent to those of the ABM20 Bolter Miner; American Joy Mining Machinery Co. Ltd. developed the 12BM18 Bolter Miner, which uses a chain-cutting drum, a coal-loading mechanism for the shovel, a crawler-type walking mechanism, equipped with 2 roof jumbolters and 2 side jumbolters for tunnel boring in rectangular roadways; Sweden Sandvik Engineering Group developed the Sandvik MB670 Bolter Miner which integrates tunnel boring and bolting, and realizes the integrated operation of cutting, loading and timbering, once-tunneling. There are more than 120 Sandvik MB670 Bolter Miners which have been applied in the market. In summary, representative machines abroad include Voestalpine ABM20, Anderson KBII, JOY12CMI5-15DDVG, 12BM18 and SANDVIK MB670.^[3-5]

2.2 Domestic Research Status

Because the foreign-developed bolter miners cannot be widely used in the complex coal seam geological conditions in China, and the equipment procurement, maintenance and repair costs are high, the domestic efforts have been made to develop the integrated tunnel boring and bolting equipment and technology suitable for most domestic roadways. Since the 1990s, China has carried out research and experiments in the field of high-speed roadway tunnel boring and bolting integration. For example, the Nanjing Research Institute of the China Coal Research Institute and the Baodian Coal Mine of the Yankuang Group Co. Ltd. jointly researched and developed the machine-mounted jumbolter, and installed it on the MRH-S100 Tunnel Boring Machine to form the integrated tunnel boring and bolting machine for testing. However, it is only a prototype of bolter miners, which is different from the actual bolter miners in foreign countries. In order to improve the mechanization level of jumbolter timbering of coal roadways, China has tried to carry out technical transformation of the existing comprehensive tunnel boring machines, and successively developed JMZ22 Machine-mounted Jumbolter matched with AM50 and S100 Tunnel Boring Machines (TBM), by installing the jumbolter on the tunnel boring machine, the bolting operation can be carried out without the need to return the machine during the tunnel boring process, which

improves the efficiency of the tunnel boring and reduces the labor intensity of the workers. However, because the configuration problem of the jumbolters is not considered at the beginning of the traditional tunnel boring machine design, the mutual interference between the tunnel boring and bolting is serious, and the application effect is poor. In the true sense, the tunnel boring and bolting machines should consider the configuration of the jumbolters from the initial stage of the tunnel boring machine design. In 2005 and 2006, China's enterprises succeeded in developing a dual-arm geophysical prospecting bolter miner and EBZ160-JM Tunnel Boring and Bolting Machine. The dual-arm geophysical prospecting bolter miner can simultaneously carry out the bolting work on the roofs and the sides of roadways. On the basis of cantilever cutting, EBZ160-JM Tunnel Boring and Bolting Machine has increased the jumbolter and front roof timbering devices, which has changed the simplification operation drawbacks of the traditional tunnel boring machine that requires re-treating, re-bolting and re-timbering. China's bolter miner products are still insufficient in the tunnel boring and bolting synchronization, the rock breaking efficiency of the cutting devices, the safety protection design of the tunnel boring and bolting and the reliability of the products, and have a large room for improvement.

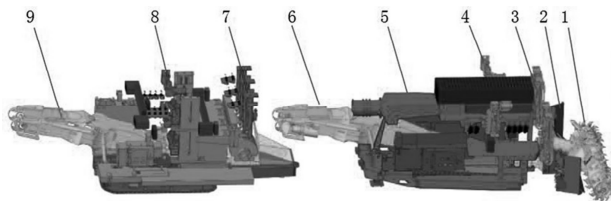
Throughout the technical research and application development of the bolter miner products at home and abroad, the integrated technology of tunnel boring and bolting has become an inevitable trend of technological development in modern tunnel boring construction.^[6-8]

3. The Characteristics and Functions of Complete Machine for High-speed Tunnel Boring and Bolting Machines

In order to solve the imbalance of tunnel boring and bolting in coal mines, carry out coal roadway construction operations safely and efficiently, focusing on mastering the key technologies and applications of coal mine roadway tunnel boring product——bolter miner, the ZJM4200 Complete Equipment for High-speed Tunnel Boring and Bolting Machines developed by China Railway Construction Heavy Industry Co., Ltd. can realize the tunnel boring and bolting synchronization and parallel operation in the true sense, which has remarkable advancement and has been successfully applied to the 5824-meter roadway of Sunying Chayi Mine in Shenmu, Shaanxi, and completed industrial tests. The overall technical performance of the prototype has reached the international advanced level.

The equipment adopts full hydraulic drive, crawler type walking, retractable drum upper and lower cutting, cyl-

independent propulsion, stepping tunnel boring method, which has the characteristics of small rock stratum destructiveness and complete synchronization of tunnel boring and bolting. The complete machine is composed of the main machine and the post-matched lining trolleys. The main machine has the main functions of tunnel boring and bolting synchronization, once-tunneling, negative pressure dust removal, digital guidance, independent cutting feed, digital cutting, safety monitoring and data interaction. The overall structure is shown in Figure 1.



Notes: 1: Cutting devices; 2: Loading devices; 3,7: Roof jumbolters; 4,8: Side jumbolters; 5: Dust removal fans; 6,9: Scraper conveyers

Figure 1. The overall structure of complete machine for high-speed tunnel boring and bolting machines

3.1 Synchronous Operations of Tunnel Boring and Bolting

The complete machine for high-speed tunnel boring and bolting machines adopts the design concept of tunnel boring and bolting both synchronization and integration, and its implementation method is as follows: the cutting drum and the jumbolter timbering devices are arranged in a reasonable division and distributed on different trolleys, and the cutting drum and the front drilling machine trolleys are used as the main machine, and when tunnel boring at working surface of the roadway, the main machine is arranged with front timbering devices. When the cutting devices of the main machine are tunnel boring, the temporary timbering devices will support the wall surface of the coal roadway to temporarily stabilize the wall surface. At the same time, the front drilling timbering machine is supported to reduce the unsupported roof distance, which effectively protects the safety of the operators. 2 side jumbolter timbering devices are arranged on the main machine when the cutting drum is tunnel boring; the coal roadway side timbering is also carried out at the same time. The timbering trolley is specially used to make up the roof and side jumbolters to achieve the effect of tunnel boring and bolting synchronization.

At the same time, by analyzing the stress distribution after coal roadway tunnel boring, the jumbolter timbering devices are reasonably arranged, and the top bolting machine, the roof jumbolters, side jumbolters and jumbolter ropes are in a dislocation arrangement to ensure that the jumbolter timbering devices do not interfere with each

other during operation. The jumbolter timbering work platform can move 1.3 meters on the chassis as a whole. The second row of side jumbolters, the third row of side jumbolters and the fifth row of side jumbolters have separate sliding functions, which can realize the jumbolter operations of any distance between rows in the range of 0.8-1 meters, which can ensure Comprehensive timbering of the entire coal roadway; the working mode of the temporary timbering of the main machine and the front synchronous timbering ensures the safety and reliability of the continuous operation of the bolter miners.^[9]

The design concept of temporary timbering, jumbolter timbering devices and the working form of jumbolter timbering devices, as shown in Figure 2, have the following advantages:

(1) The tunnel boring and bolting are carried out simultaneously, and anchoring do not interfere with each other, and the roof and two sides of the coal roadway are timbered in time to realize high-speed and continuous tunnel boring of the coal roadway.

(2) The integration of the tunnel boring and bolting is carried out simultaneously, which reduces the auxiliary working time. By controlling the deformation of the surrounding rocks in time, the supporting operation can be completed without the need to retreat the machine, which greatly improves the tunnel boring speed of the coal roadway.

(3) It can provide large temporary timbering force in time, so that the integrated tunnel boring and bolting machine is under the protection of the safety of the timbering to ensure the safety of the construction personnel.

(4) It has low requirements on the bearing capacity of the footwall, and the crawler does not move in place when undermining and does not damage the footwall.



(a) The tunnel boring of main machine



(b) The post-matched timbering

Figure 2. Synchronous operation of tunnel boring and bolting

3.2 Once-tunneling

The tunnel boring system of complete machine adopts a retractable high-power, low-speed cutting drum structure, and the cross-section can be rectangular or arched (the drum-shaped cutting drum needs to be replaced when meeting the arched roadway). When tunnel boring, the chassis does not move; the cutting devices are advanced by the undermining oil cylinder to realize the cutting feed. The maximum one-time advance is 1 meter, and the cutting is completed into a once-tunneling roadway. The disturbance to the rock layer is small, and the quality of the roadway is high. In order to adapt to different specifications of coal roadways, the cutting drum stretchable width range covers 4.9m-6.2m, and can also be customized design; the roadway height covers 3.2m-5.5m. The structure is shown in Figure 3.

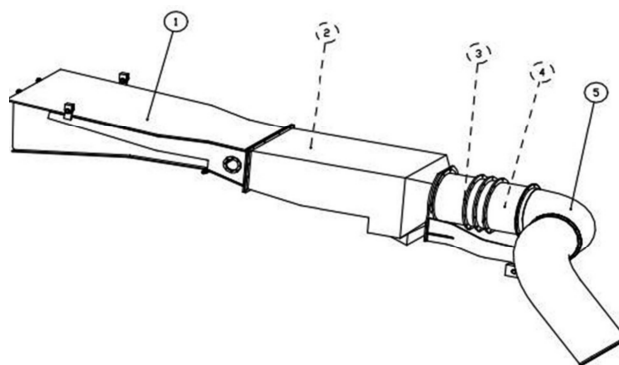


Figure 3. Once-tunneling

3.3 Negative Pressure Dust Removal

The dust removal system is designed to ensure the clean working environment in the coal roadway (as shown in Figure 4). The complete machine adopts semi-closed negative pressure dust removal and spray dust reduction system (as shown in Figure 5). The dust is effectively isolated from the operators, and the dust generated during the cutting process is sucked into the dust collector by negative pressure dust removal fans, and the dust removal capacity is up to 300 m³/min. The coal water discharged after the

dust removal by the dust removal fan directly enters the scraper conveyor and is transported to the transportation system along with the coal flow. The semi-closed negative pressure dust removal system improves the air quality in the working area and ensures the occupational health of the workers.



Notes: 1: Exhaust inlet; 2: Dust remover; 3: Fans; 4: Hydraulic motor; 5: Air pipes

Figure 4. The dust removal assembly units



Figure 5. Semi-closed negative pressure wet type dust removal system

For the negative pressure dust reduction technology, the main factors affecting the performance are the water supply pressure, the ventilation volume, the performance and position of the nozzle. The requirements for the fan during the construction operations of Bolter miner are very strict. The resistance of the ventilation system is an important parameter basis for determining the wind pressure of the fan. The air flow in the duct in the ventilation system produces two kinds of resistance: one is the resistance along the path, which is caused by the friction between the internal viscosity of the air and the wall of the ventilation duct, and the resulting energy loss along the path; the other is local resistance, which is generated by the eddy current generated when air flows through the elbow in the air duct and at the variable diameter, and the energy loss generated locally is concentrated. Fan wind pressure is used to over-

come the above two resistances to ensure that the required design air volume is delivered to the working area.^[10]

The complete equipment for high-speed tunnel boring and bolting machines adopts the above semi-sealed negative pressure dust removal combined with the principle of spray dust reduction, combined with theoretical analysis to design the ventilation dust removal device, effectively solve the dust removal problem and improve the working environment. The drum is equipped with an internal and external spray system, and the dust reduction effect can reach 80-90%, which is the first dust removal function. After dust removal, the dust concentration is still high, and a second dust reduction treatment is required. In the process of powder propagation and diffusion, it is captured and extinguished, namely, the vacuum flow of the roller end face is absorbed and purified by the negative pressure secondary dust reduction technology, thereby achieving the purpose of dust reduction. The dust removal structure separates the cutting section from the worker's operation area, and adopts imported wet dust-reducing equipment. The dust treatment capacity is 300m³ /min, and the dust removal field application works well with bolter miners.

3.4 Digital Guidance

Figure 6 shows top and side cross-sectional views of the roadway.

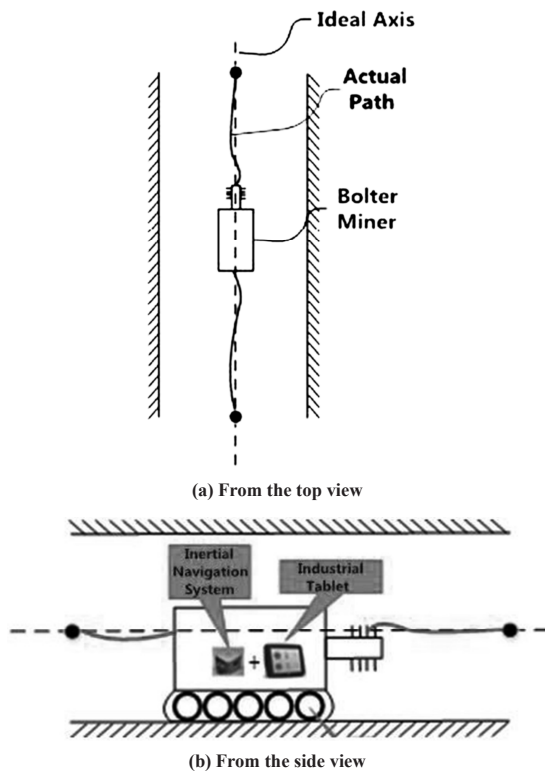


Figure 6. The top and side cross-sectional views of the roadway

As can be seen from Figure 6, when the bolter miner is advancing in the roadway, between the actual path of body axis and the ideal axis of the roadway, angular deviations in the three dimensions of pitching, roll and heading are inevitable. As the mileage of the bolter miner advances, the actual motion track will deviate from the ideal axis in the space coordinates of the roadway. The main purpose of the system (Figure 7) is to obtain the three-dimensional offset of the vehicle body and the absolute three-dimensional coordinate data (with the initial alignment of the total station) as the control input for the mileage advancement of the bolter miner to ensure that the actual propulsion trajectory of the bolter miner and the error of the ideal roadway axis are controlled within the threshold range allowed by the tunnel boring and bolting process.

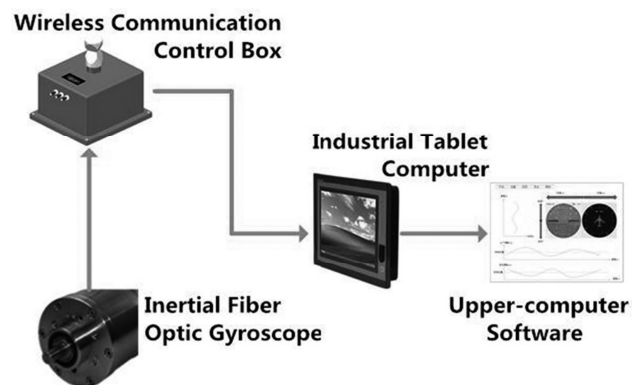


Figure 7. Automatic guidance system

The automatic guidance system of the device is mainly composed of: RMS-D automatic guidance system software, inertial fiber optic gyroscope, wireless communication control box, industrial tablet computer (pre-installed software), and dedicated power supply cable. The device adopts digital gyroscope inertial navigation technology to break the traditional discontinuous measurement method, constructs a three-dimensional coordinate model of the state of the anchoring machine, senses the state of the bolter miner, and combines the inertial guidance technology with the sensor measurement to realize the automatic positioning, rectification, remote control and automatic monitoring functions of the anchoring machine.

The system displays the offset in real time, which can accurately control the midline offset of the roadway, and the roadway tunneling deviation is $\leq 5\text{cm}$. It has the following main characteristics and advantages (Figure 8):

(1) The measurement accuracy of the core inertial measurement unit and the stability of the long-term work index are improved, and the system index is improved in essence, and the continuous precision maintenance of 300m without manual correction is realized.

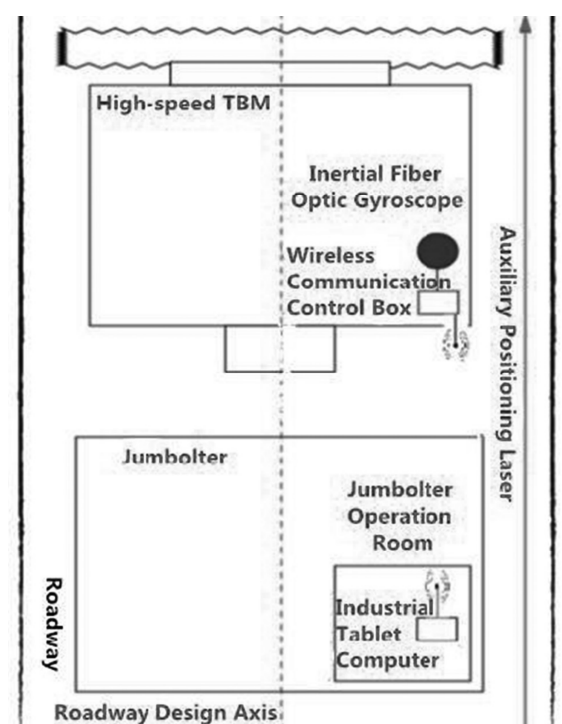
(2) The navigation information is abundant, which can

independently give all the high-precision information needed to realize automatic guidance, including: real-time attitude and heading, and three-dimensional translation data in the roadway coordinate system.

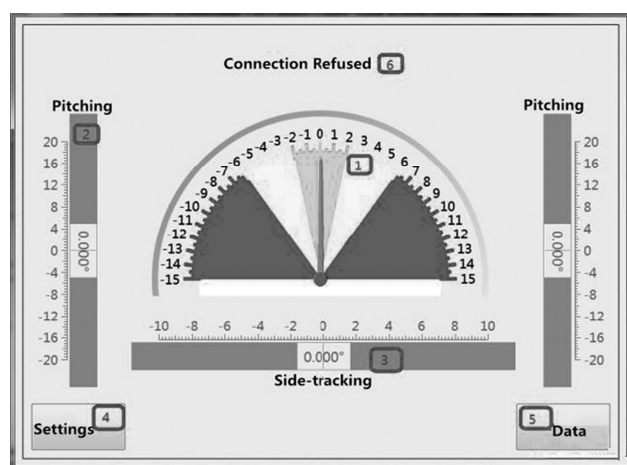
(3) It is tightly coupled with the data of system sensors such as encoders, and uses the inertial navigation information to automatically correct and compensate the disturbance errors such as track slip and idling, and the data of the system sensors participate in the inertial navigation solution.

(4) It has visual human-computer interaction with easy operation and low threshold.

(5) Optical measurement assisted calibration to further improve the overall guiding accuracy of the roadway.



(a)



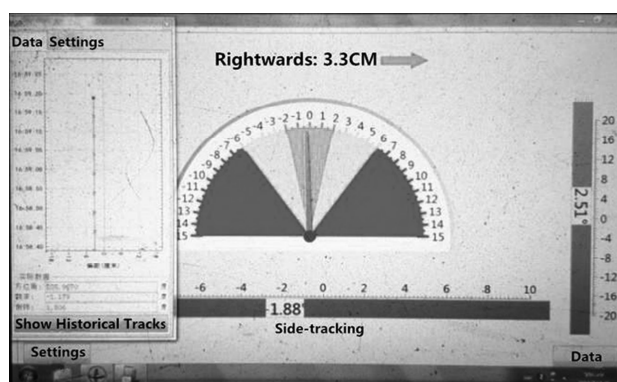
(b)



(c) Digital gyroscope — precise guidance



(d)



(e)

Figure 8. Guidance control equipment and man-machine interfaces

3.5 Safety Monitoring

At present, the safety production status of China's coal is still not optimistic. In many coal mine safety accidents, there are many inducing factors. However, the incomplete

monitoring equipment for harmful gases in the coal mine production process and the backward warning technology are one of the important factors causing accidents. Harmful gases are methane, carbon monoxide, carbon dioxide, dust, etc. When the gas concentration in the air reaches 5%-16%, it will explode when it encounters a certain ignition energy (usually caused by electrical sparks, accounting for 50% of the total fire). When there is coal dust in the mixed gas, the lower explosion limit is lowered. The proportion of various gases is different, and the accidents caused are equally deadly. Therefore, the monitoring and early warning system for harmful gases is an important management tool for controlling gas accidents, which can not only accurately detect the content of harmful gases, but also automatically issue an alarm when the measured harmful gas concentration exceeds a predetermined value, reminding the staff to stop working or leave immediately, so that the coal mine can take targeted preventive measures. In addition, it also immediately cuts off power in hazardous areas to avoid accidents. Therefore, real-time detection of methane, carbon monoxide, carbon dioxide, dust and other harmful gases in the underground air environment, as well as early warning is necessary.^[11]

The complete equipment for high-speed tunnel boring and bolting machines has a set of digital, intelligent and automated monitoring and early warning system for harmful gases, which is equipped with a comprehensive methane detector, carbon monoxide sensor, infrared carbon dioxide sensor, dust concentration detector and other sensors to perform real-time, continuous and comprehensive monitoring of the main harmful gases (Figure 9). At the same time, through data acquisition, the main control

system of the equipment performs data analysis, display, alarm, active braking, etc., and pre-processes and forecasts the upcoming danger (Table 1). In accordance with the requirements of the coal mine safety regulations, the “three special & two locks” (Special transformer, special cable, special switch; wind power lock, gas lock) were implemented to ensure the safety of the operators. At the same time, the sensor has good stability, strong anti-interference ability, small monitoring error, and few false alarms. The prediction and production do not affect each other, which provide a powerful guarantee for improving production efficiency under safe and reliable production conditions.^[12]

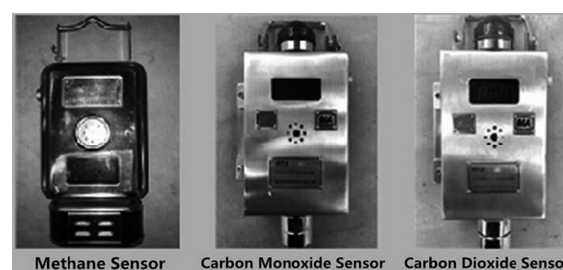


Figure 9. Gas sensors

The complete equipment for high-speed tunnel boring and bolting machines is also equipped with a combined amplified telephone with voice alarm function. The combined amplified telephone is intrinsically safe and is suitable for use in coal mines with coal dust and explosive gas. Up to 15 alarm sounds can be prepared according to site requirements. In addition, the combined speakerphone has two LED displays for light alarms. When the methane, dust and other harmful gases in the excavation site exceed the standard, the voice alarm function of the combined

Table 1. The Characteristics of gas sensors

Product Name	Explosion-proof Form	Testing Range	Measuring Errors	Response Time
Methane Sensor	Mining Intrinsically Safe	0 ~ 10.0%	00.00 ~ 1.00% $\leq\pm 0.10\%$ 1.00 ~ 3.00% $\leq\pm 10\%$ 3.00 ~ 4.00% $\leq\pm 0.3\%$ 4.00 ~ 10.00% $\leq\pm 10\%$	20s
Mining Carbon Monoxide Sensor	Mining Intrinsically Safe	0 ~ 500 ppm	0.00 ~ 100.0ppm $\leq\pm 4\text{ppm}$ 100 ~ 500 ppm $\leq\pm 5\%$	35 s
Infrared Mining Carbon Dioxide Sensor	Mining Intrinsically Safe	0 ~ 5.00%	0.0~0.50% $\leq 0.10\%$ 0.5~5.00% $\leq\pm 0.05\%+5\%$ truth-value	30s
Mining Dust Sensor	Mining Intrinsically Safe	0.01 ~ 1000mg/m ³	$\leq\pm 2.5\%$	20s

amplified telephone will emit methane exceeding the standard. Please pay attention to the dust, please pay attention to the voice prompts, and issue a light alarm.

4. The Application of Complete Equipment for High-speed Tunnel Boring and Bolting Machines

The equipment has achieved good results after being used in Sunying Chayi Mine in Shenmu, Shaanxi.

The main roadway of the mine adopts a rectangular section with a sectional area of $5.2 \times 3.2\text{m}$, a hardness of coal seam f4, a density of coal seam of $1.28\text{--}1.3\text{t/m}^3$; the timbering method is arranged as 4 roof jumbolters and 3 side jumbolters on each side. This complete equipment for high-speed tunnel boring and bolting machines has completed the footage of 5824m, the highest daily footage is 92m, and the highest monthly footage is 2425m, the coal tunnel boring speed is high, and the labor intensity is low; it is also safe, reliable and efficient. The construction site is shown in Figure 10.

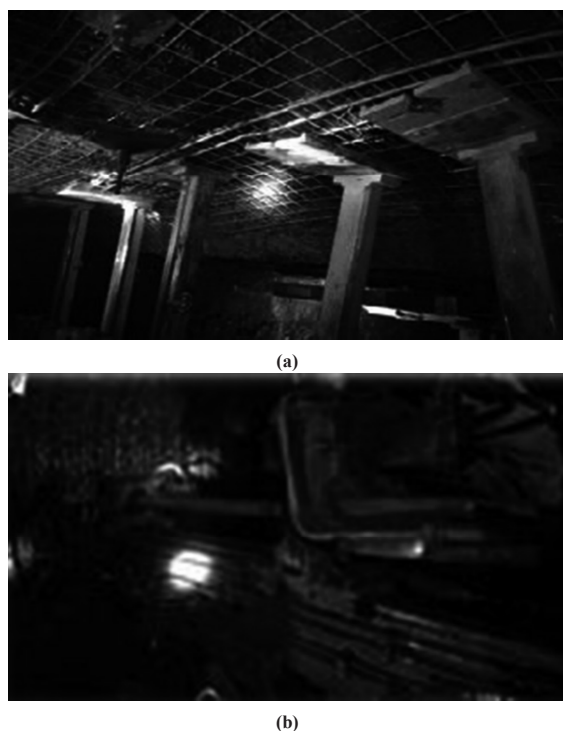


Figure 10

5. Conclusion

The successful development of this complete equipment for high-speed tunnel boring and bolting machines has filled the blank of the domestic integrated technology of tunnel boring and bolting, which has greatly promoted the

market application of the domestic complete equipment for high-speed tunnel boring and bolting machines. Its successful development is of great significance to improve the mechanization level of coal mine construction and the safety, reliability and efficiency of construction.

(1) The synchronous operation of tunnel boring and bolting has been realized, which solves the key problem that the tunnel boring and bolting cannot be synchronized, greatly improves the efficiency of the roadway tunneling, breaks through the technical bottleneck of coal mine mining imbalance, and significantly improves the high-speed tunnel boring level of coal mine roadways under complex geological conditions.

(2) The use of negative pressure dust removal, digital cutting and other technologies has greatly improved the construction environment, improved the speed of coal roadway tunnel boring, ensured the safety of coal roadway tunnel boring, and reduced the labor intensity.

(3) The three-dimensional coordinate model of the state of the bolter miner is constructed. The sensor, automatic detection and positioning and rectification technology are used to realize the automatic positioning, remote control and automatic monitoring of the bolter miner, which improves the intelligent level of the bolter miner, provides a theoretical and practical basis for the development of intelligent bolter miners.

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