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Non-explosive mechanized and intelligent mining/heading in underground mine

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Abstract: The non-explosive mechanized mining and heading is an alternative approach to traditional drilling and blasting method for excavating the deep hard rock, the intellectualized upgrade of which includes smart perception, wise decision and intelligent control. Based on the comprehensive analyses for two key problems (rock breakage and rock stability) and three key factors (environmental conditions, rock properties and excavation parameters), the process of non-explosive mechanized and intelligent mining and heading was established, which included in-situ monitoring, cuttability improvement, intelligent control and performance evaluation to achieve mechanization, automation and unmanned fully-automation for equipment, continuation, refinement and collaboration for process, and informatization, digitization and smartization for management. In addition, the PDCA (Plan−Do−Check−Adjust) cycle and its associated sub-cycles were established to manage the process of non-explosive mechanized and intelligent mining and heading. Through the cyclic managements for deep high stress induced utilization and energy regulation, mutagenesis modification for risk reduction and cuttability improvement of hard rock, and multi-source rock breakage, the safe and efficient mining and heading in underground mine can be achieved.
Key words: deep mining; non-explosive mechanized excavation; intelligent mining and heading; mining and heading processes; management model

1 Introduction

The exploitation of mineral resources is very important to the economic development of modern society. According to the statistics, 80% of the raw materials needed for social production, 90% of the energy and 70% of the means of agricultural production come from mineral resources [1]. However, from the perspective of industrial mining production, there are the inevitable environmental problems and personal safety risks with increasing the depth of mining. Approximately 90% of metal mines in China are underground mines. The 40% of underground metal mines built from the 1950s are gradually transitioning to deep mining. Therefore, in the process of mineral resource development, it is necessary to pay attention to the three themes of safety, efficiency and green. First of all, various measures should be taken to prevent accidents to ensure production safety and environmental safety. Secondly, there is a need to improve efficiency and quality of mining production to reduce costs and promote competitiveness. Finally, on the premise of ensuring environmental friendliness and low carbon health, it is necessary to avoid over-exploitation and waste of resources.

However, in the actual production process, there is a mutual restriction relationship between efficiency and safety. If the pursuit of economic rationality is considered only, the corresponding security will be reduced and vice versa. Similarly, there is a similar restrictive relationship between the green and safety. On the one hand, emphasizing

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environmental protection and healthy low carbon, we must consider how to eliminate the potential risks and health problems of the environment and human body. On the other hand, the constraint relationship between the green and efficiency, resource conservation and sustainability needs to consider the balance and trade-off of factors at all times. Therefore, it is necessary to comprehensively consider various factors to balance interests and needs, and ultimately achieve safe, efficient and green development, as shown in Fig. 1.

As a new mining method, the intelligent mining is one of the important means to promote the development of efficient, safe and green mining [2,3]. Compared with traditional mining methods, intelligent mining has the advantages of higher efficiency, lower cost, safer environment and more sustainable development. Through sensor monitoring, data analysis, and automated control technology, the processes of mining, separation, and smelting are optimized to increase mineral recovery rates while reducing resource waste and energy consumption, thereby achieving efficient mining. Automation and remote control technology can replace high-risk manual operations, reducing the associated risks and enhancing mining safety. In-site monitoring technology facilitates the prompt identification of potential risks and hazards in the production process, leading to improved workplace safety. Additionally, the coordinated control of the mining process through the monitoring of environmental parameters (air quality, water quality, and rock quality) contributes to reducing the generation of tailings, waste rock, and harmful gases, thus achieving environmentally responsible mining.

To sum up, intelligent mining can not only achieve efficient, safe and green development of mining production, but also combine with traditional mining methods to promote industrial upgrading and innovation. In the future mining development, intelligent mining is undoubtedly one of the indispensable and important components.

2 Challenges of deep mining

The development status of mineral resources shows that with the gradual depletion of shallow mineral resources on earth, the number and depth of deep mining mines increase rapidly, and deep mining of mineral resources will inevitably become normal in the future [4]. From the perspective of resource exploitation around the world, the mining depth of coal exceeds 2000 m, and the deep level gold mine with the largest mining depth of nonferrous metals has reached 4800 m [5]. According to incomplete statistics [6,7], there are 47 coal mines and 22 metal mines in China with a mining depth of more than 1000 m, and the deepest mining depth of Henan Qinling Gold Mine reaches 1990 m. In the near future, 30% of the mines will enter deep mining, and will extend downward at a rate of 10−25 m/a. As shown in Fig. 2, there are two key problems, such as rock breakage and rock

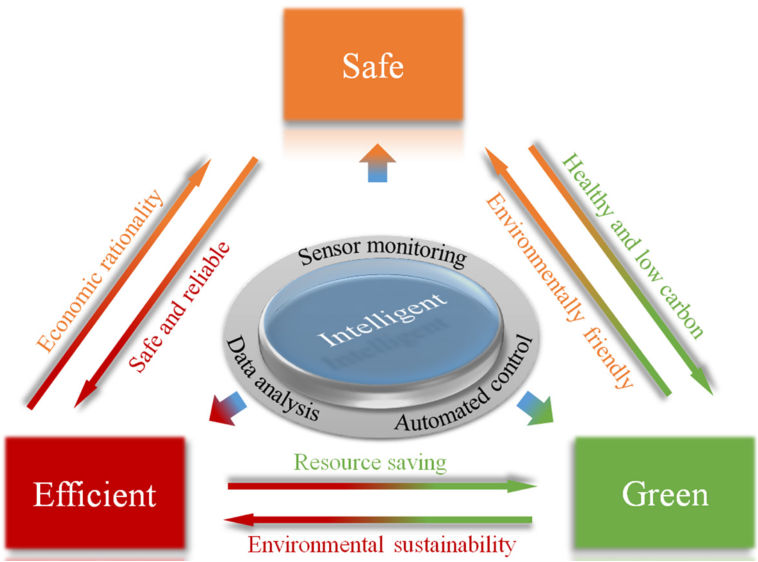


Fig. 1 Safe, efficient, green and intelligent collaborative mining mode

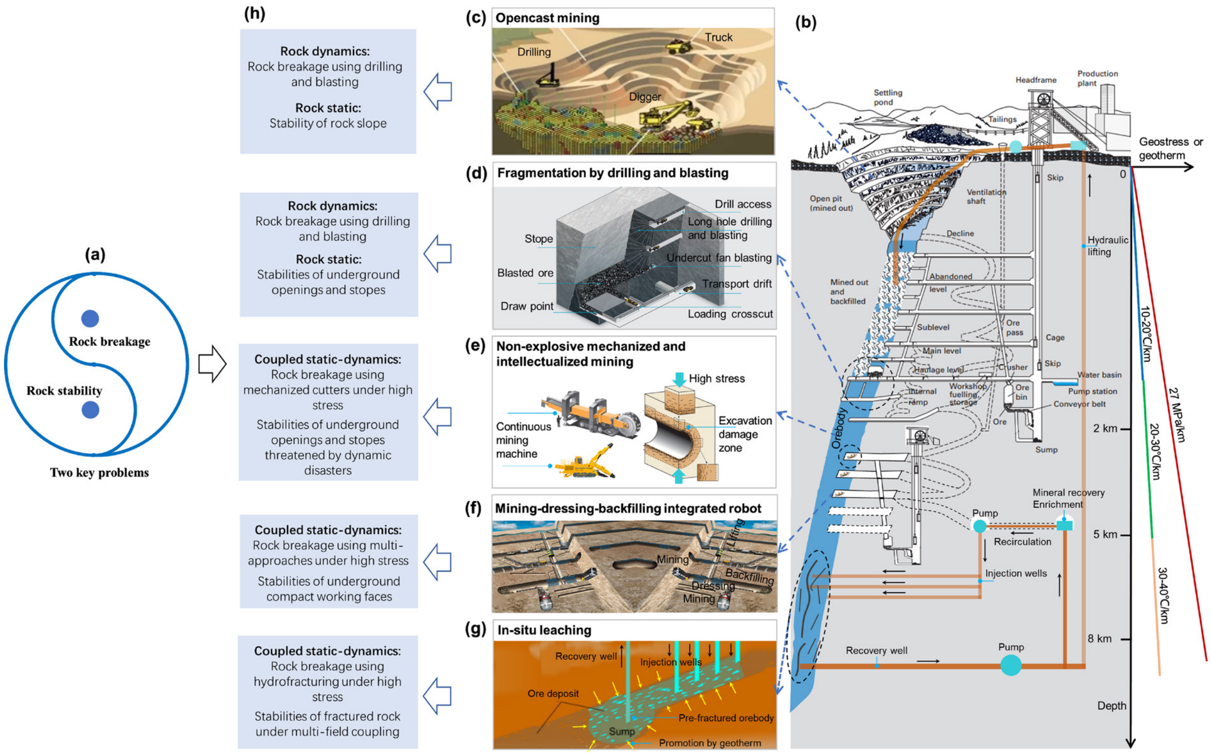


Fig. 2 Two key problems that should be addressed in different mining stages from ground surface to deep underground: (a) Relationship between rock breakage and rock stability; (b) General mining layout; (c) Opencast mining; (d) Shallow mining by drilling and blasting; (e) Non-explosive mechanized and intellectualized mining in deep underground; (f) Mineral exploitation by mining−dressing−backfilling integrated robot in deep underground; (g) In-situ leaching in ultra-deep underground; (h) Different rock breakage methods and rock stability considerations for different mining stages

stability, which should be addressed in mineral resource mining for the different mining stages from ground surface to deep underground. For the opencast mining and shallow mining by drilling and blasting, the rock is subjected to the single load, such as dynamic load for blasting-based rock breakage or static load for influencing rock stability. For the deep underground mining, the rock is subjected to the coupled static−dynamic loads, for example rock breakage using mechanized cutters and the multi-approaches (water jet, laser, microwave, etc) under high stress and rock stability threatened by dynamic disasters (rockburst, large-scale deformation, slabbing, zonal disintegration, etc) induced by high stress and dynamic disturbances. For the ultra-deep mining, the rock is subjected to the coupled static−dynamic load and multi-field coupling interaction, for example rock breakage using hydrofracturing under high stress and the stability of fractured rock under multi-field coupling.

With more and more deep mineral resources being mined, deep rock mining faces many challenges. These include three key factors, such as environmental factors, rock mass conditions and mining parameters, which affect mining efficiency and safety to varying degrees (Fig. 3). The details are as follows:

(1) Environmental factors are composed mainly of the generally recognized “three highs”, including high in-situ stress and the associated dynamic disturbance and stress redistribution induced by rock excavation, high temperature and high water pressure [8]. In addition, multi-field coupling and multi-phase coexistence environments also place higher requirements on the selection and design of mining sites and mining equipment. When the mining depth exceeds 1000 m, the in-situ stress can reach 40−80 MPa, the rock temperature exceeds 40 °C, and the water pressure also reaches 10 MPa [9]. Under high in-situ stress, the deformation energy of deep rock mass is highly

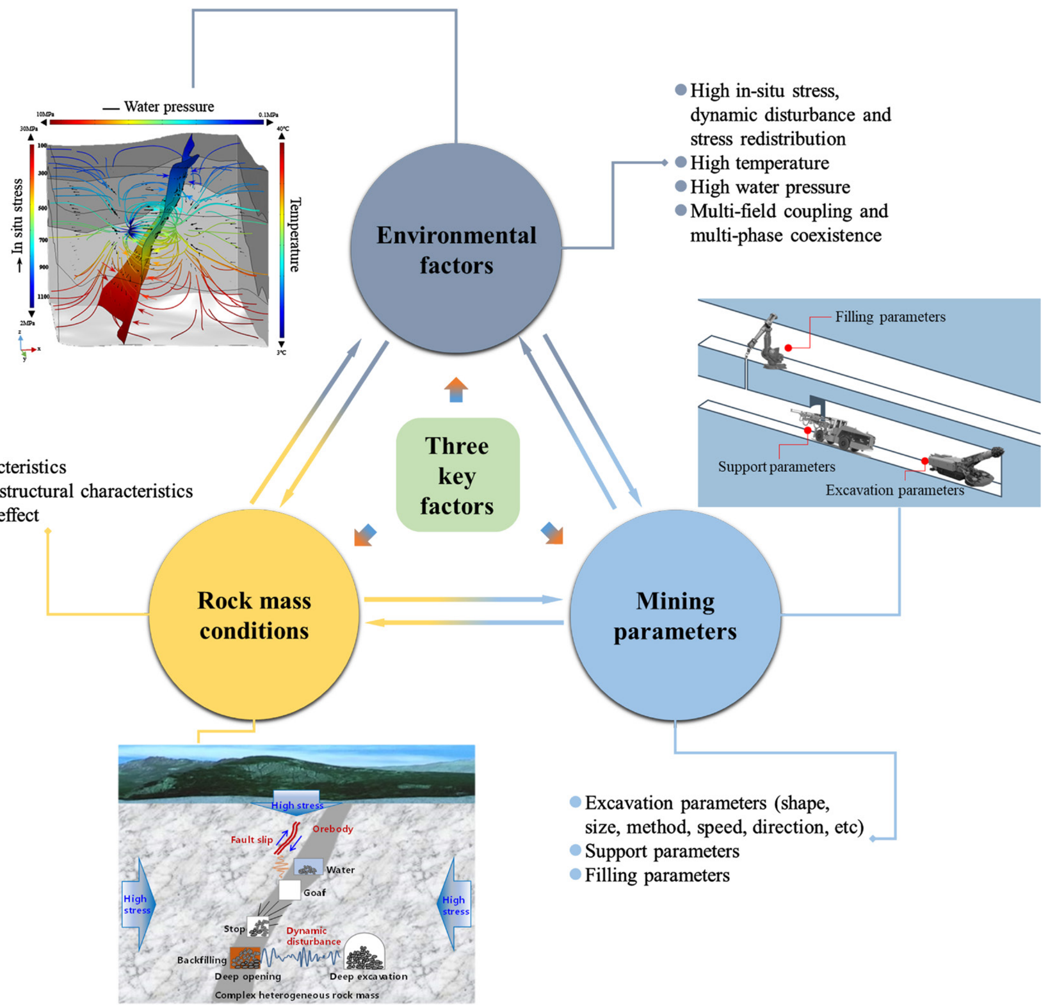


Fig. 3 Influence factors for deep mining and associated relationships

accumulated, and dynamic disasters such as rock bursts are easy to occur. At high temperatures, the operation environment of workers is poor, and the accidents such as spontaneous combustion of high sulphur ore and explosive self-detonation occur easily. High water pressure may promote the development of cracks in rock mass and cause disasters such as water inrush and fault instability. At the same time, under the combined action of strong mining disturbance and strong rheology, deep mining is actually a complex physical and mechanical process in which solid, liquid and gas coexist under the coupling of high stress field, high temperature field and high seepage field. The above deep environmental factors will lead to more frequent engineering safety accidents and pose a serious threaten to the safety of mining operations.

(2) Rock mass conditions are composed mainly of three parts: rock characteristics, rock mass structural characteristics and multiscale effect. Rock characteristics include rock physical properties (density, specific gravity, pore ratio, water content, water absorption, specific heat capacity, etc), strength properties (uniaxial compressive strength, tensile strength, shear strength, triaxial compressive strength, etc), deformation properties (elasticity, plasticity, viscosity, rheology, etc). The combination of structural plane and structure element in different forms is usually called rock mass structure. The characteristics of rock mass structural plane can be divided into natural characteristics and mechanical characteristics. Natural characteristics are usually characterized by spatial distribution characteristics (attitude, density, and continuity), morphology, opening degree, and filling and cementation. The mechanical characteristics mainly include normal deformation, tangential deformation and shear strength. Multiscale effect refers to the fact that rock mass structural problems and various

geological problems have different scales and levels when mining deep rock mass, involving the span of mineral microscale to structural macroscale [10]. Interaction between different scales can lead to changes in mining conditions. For example, geological structures of different sizes, such as joints, cracks and faults, exist in geological bodies. Under the tectonic action of different scale and type of force sources, the distribution of geological stress fields shows obvious multiscale effect [11]. In short, the mining-disturbed rock mass is a complex heterogeneous medium, including different materials (rock, backfilling, water, space, etc) and multiscale structures (goaf, fault, stratification, joint, crack, contacts, etc) under the coupled static and dynamic loads. The above rock mass conditions, from microscopic mineral composition to macroscopic structural characteristics, affect the stability and failure characteristics of rock mass, and determine the degree of mining difficulty.

(3) Mining parameters include excavation parameters, support parameters and filling parameters. Among them, the excavation parameters are divided into excavation structure shape and size, excavation method, excavation direction and so on. Excavation parameters need to be scientifically designed according to the actual geological conditions [12]. If the excavation parameters are not designed correctly, it may lead to low mining efficiency and even cause accidents such as rock collapse. In addition, the mining-formed goaf destroys the original equilibrium stress field, and the stope is prone to sudden instability. Especially in a high in-situ stress environment, the potential harm is increasing. Support and filling are the key means to ensure the stability of the surrounding rock mass. Common support means for underground mining include anchor bolt, shotcrete, arch frame and forward support. When the support means are determined, the design of the support parameters will directly affect the support effect and economic effect. Filling methods include dry filling, water sand filling, cemented filling, paste filling, etc. Selecting a reasonable filling method and filling ratio is the key to filling parameter design.

These factors are the main challenges facing deep rock mining. Among them, environmental factors and rock mass conditions will directly affect the design of mining parameters, which in turn will lead to the changes in the engineering structure of rock mass conditions and cause the stress redistribution and dynamic disturbance of environmental factors. In addition, environmental factors and rock mass conditions are interdependent and interact with each other. The rock mass conditions will affect the carrying capacity of environmental media such as groundwater and gas. At the same time, environmental factors will also affect the stability and mechanical properties of rock mass.

Therefore, deep rock excavation requires scientific environmental monitoring and rock mass monitoring. According to different environmental and rock conditions, the excavation parameters are designed and optimized to ensure the safety and efficiency of deep mining. In addition, with the continuous development of modern technology, it is necessary to develop new and advanced technical means for deep mining exploration to better cope with the uncertainty and risk in deep mining.

3 Non-explosive mechanized and intelligent mining and heading

For deep mining in underground mine, there are two key operations for rock excavation to produce the working space for drilling, blasting or cutting, loading, transportation and ventilation, including the enterway heading and stope mining. The level of mining and heading technology determines the deep mining development. To address the mineral demand mentioned earlier and overcome the obstacles associated with deep mining, it is crucial to explore and implement intelligent mining. Intelligent mining is a comprehensive field, covering technology, equipment, process and management. From the systematic analysis of the perception, decision and control involved in the mining and heading process, in-situ acquisition of geological multidimensional information technology, excavation support integration technology, non-explosive mechanized mining and heading of hard rock technology, whole process monitoring and guarantee technology, intelligent collaborative control technology and other technologies are the key frontier technologies for realizing intelligent mining at present, and are also the inevitable trend for the mining and heading development in the future [13−16]. The intelligence degree of equipment continues to improve, gradually developing from the initial manual operations to mechanization, automation and unmanned operation. At the same time, benefitting from the increasingly high quality, efficiency and environmental requirements of mining, traditional independent production is changing to the directions of continuity, refinement and collaboration. In addition, in terms of management, the rapid development of information and digital technology has promoted the transformation of management mode from informatization and digitalization to wisdom.

These aspects complement each other and are expected to form an intelligent mining cycle of intelligent perception, intelligent decision-making and intelligent control (Fig. 4). For example, in the mining process, the equipment can automatically perceive the surrounding environment like the human brain and make the most appropriate judgment based on the data, thus enabling intelligent decision-making. The results of mining are fed back to the manager in real time to continuously optimize the operating status of the entire mining system to achieve efficient, safe and sustainable intelligent control. In short, intelligent mining is a field of continuous development and innovation, and it is necessary to constantly introduce new technologies, establish an open collaborative process, and promote the development of management.

3.1 Mining and heading technology

In the field of mining and heading technology, it primarily focuses on the advanced detection, heading, mining, support, monitoring, control and other related aspects. The descriptions of the different technologies are given below.

(1) In-situ acquisition of geological multi-dimensional information technology

In general, the drilling method and geophysical method are employed for advanced detection to gather information on the geological and hydrological conditions of the excavation working face. With the development of data transmission and analysis technology, these methods can also be utilized to assess the stability of surrounding rock and determine the distribution of rock cuttability, drillability and anchorability. Future research should focus on developing the monitoring while drilling (MWD) technology, high-precision measurement while drilling system and intelligent drilling robot technology [17]. Geophysical methods vary depending on the construction method (drilling and blasting or tunnel boring machine) and the environment (coal roadway or rock roadway), but commonly include seismic methods, direct current methods, transient electromagnetic methods, and others [18,19]. To achieve intelligent advanced detection technology, it is crucial to conduct research on seismic monitoring while tunneling of heading machine or

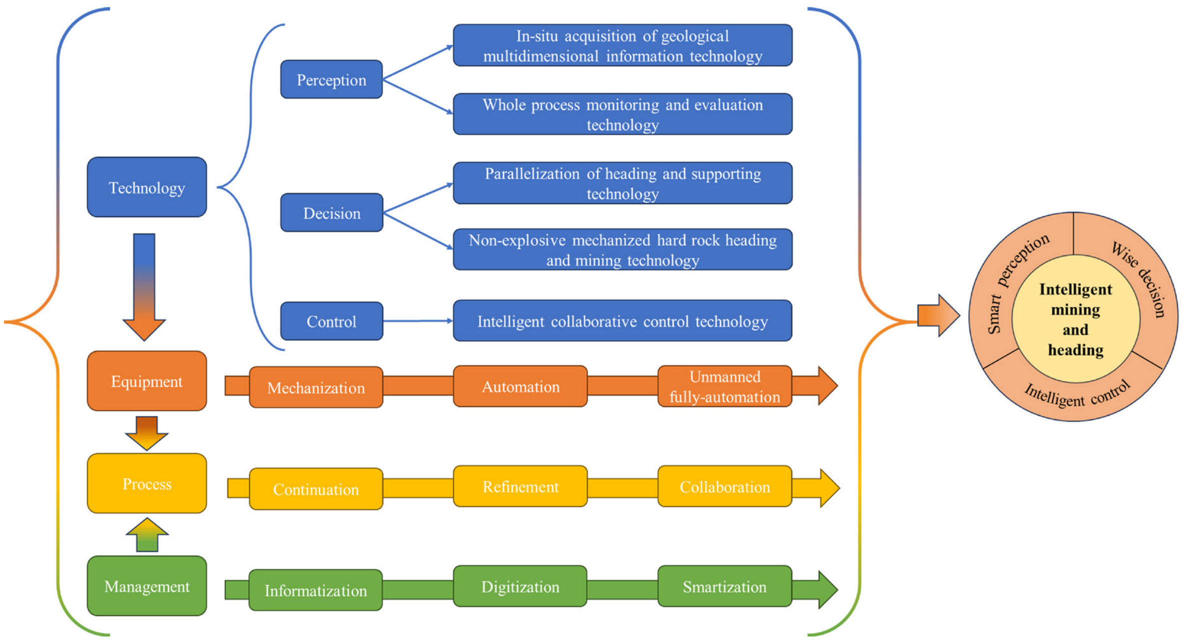


Fig. 4 Structure diagram of intelligent mining and heading

tunnel boring machine (TBM), borehole transient electromagnetic technology and bore-tunnelling electrical ahead monitoring (BEAM) method. In summary, the in-situ acquisition of geological multidimensional information technology serves as the primary data source for realizing pre-excavation geological prediction and risk assessment. It is the basis for ensuring mining safety and acts as a prerequisite for realizing intelligent mining technologies.

(2) Parallelization of heading and supporting technology

Heading and support are two important production processes in excavation. They are also the largest in terms of workload and the most challenging in work environment. Traditional excavation methods involve alternating heading and support operations, which are inefficient and unsafe. Excavation equipment is typically single-functioned and lacks coordination, limiting efficient mining production and intelligent development. To achieve rapid and safe excavation, researchers have started studying parallel heading and support technologies, making certain progress in heading and bolting integration technology and temporary support technology [20]. Heading and bolting integration technology is to integrate heading and bolting functions on the same equipment, supported by transport equipment, enabling synchronous operations of rapid heading, support and transportation. It mainly consists of boom-type roadheader with jumbolter and bolter miner. Generally, the appropriate excavation mode is selected based on different geological conditions. For stable and moderately stable tunnels, bolter miner is used. For unstable tunnels, boom-type roadheader with jumbolter or temporary support can be employed [21]. Representative temporary support solutions include advance beam temporary support, onboard temporary support, and self-moving temporary support [22]. However, there are disadvantages such as cumbersome cyclic steps, inconvenient construction, and lack of systematic and comprehensive approach. In the future, there is a need to overcome passive temporary support methods by developing the technology and materials of thin film temporary support and automatic spraying equipment to realize the technical change of temporary support.

(3) Non-explosive mechanized hard rock heading and mining technology

Unlike the fully mechanized mining technology widely used in coal mining, the mining method of metal mines is still dominated by drilling and blasting due to the hard rock and its associated strong abrasive properties. Although drilling and blasting method has the advantages of mature technology, high applicability and low cost, it also has obvious disadvantages, such as high risk, low energy utilization rate, large derivative damage, slow intelligent process and other problems, which are difficult to satisfy the safe, high efficient, green and intelligent needs advocated by deep mining [23,24]. Therefore, experts and scholars have proposed to replace the traditional drilling and blasting method by non-explosive methods, which mainly include mechanized rock breakage, hydraulic rock breakage, microwave rock breakage, thermal impact-based rock breakage, expansion rock breakage and combined rock breakage [25]. Among them, the non-explosive mechanized rock breakage technology has the advantages of high safety, low cost, high production efficiency, good working environment, low labor intensity, high resource recovery rate and small derivative damage compared with the drilling and blasting method, which is the most feasible method for deep hard rock breakage [26−28].

(4) Whole process monitoring and evaluation technology

Monitoring and evaluation throughout the entire process of mining is a key means of ensuring mining safety. In response to the needs of intelligent mining and geological protection, important evaluation indicators faced during the mining process have been analyzed, including a comprehensive, accurate, real-time, and multi-source data rock stability monitoring system, transparent geological modeling, and dust concentration monitoring, etc. Rock stability monitoring can be divided into two categories: local monitoring technology and system monitoring technology. Local monitoring technologies include core logging, stress measurement and surrounding rock deformation monitoring. System monitoring technologies include electromagnetic radiation, acoustic emission, microseismic monitoring and vibration tomography [29]. Due to the complex underground environment, different monitoring technologies have applicable ranges in different scales of monitoring and are subjected to the objective factors such as technical conditions, regional scope, and environmental information. Therefore, a single monitoring technology is difficult to reliably analyze the stability of surrounding rock, and the use of computer technology to construct a multi-source monitoring system has become an urgent problem to solve in the future [30]. Key technologies for transparent geological modeling include integrated exploration and measurement techniques, geological modeling techniques, CT slicing techniques, and dynamic updating techniques [31]. In addition, technologies such as precise geophysical exploration, real-time detection during mining, and machine vision need to be further researched. Monitoring factors such as dust concentration, support safety, tool wear and rock fragmentation effects also need to change from traditional discrete equipment monitoring to online monitoring and achieve integration with other monitoring systems.

(5) Intelligent collaborative control technology

In underground mining, the interaction among major equipment such as supports, mining machines, and conveyors, along with the simultaneous operation of hundreds of subsystems including communication, sensing, and control, has resulted in the formation of increasingly complex and intelligent systems. The progress of intelligent technology in individual equipment systems alone cannot achieve the desired outcome. It is necessary to consider each equipment and system as an organic whole and implement intelligent collaborative control technology [32]. For instance, collaborative control systems such as roadway support−modification−unloading, comprehensive spatial control of deep tunnels, and underground all-dimensional digital perception system based on “hierarchical extraction−correlation analysis−virtual to real mapping” have been developed [33,34]. Approaches for multitasking include reinforcement learning-based parallel operation control methods and agent-based parallel control methods, while for multiple systems, leader-follower approach and behavior-based approach are mainly utilized [35]. Intelligent collaborative control technology can break down the data barriers between equipment and systems, and integrate data of mining geological information, production status and mining equipment status to enhance and optimize operational decision-making.

In summary, the perception encompasses the in-situ acquisition of geological multidimensional information technology, as well as the whole process monitoring and evaluation technology. The former requires the development of new drilling and geophysical technologies in the future to achieve real-time geological prediction during mining and heading. Furthermore, in the entire process, the integrated environmental monitoring will be implemented by combining sensors and computer technology. In terms of decision, the parallelization of heading and supporting technology and the non-explosive mechanized hard rock heading and mining technology for hard rock require the development of fast temporary support systems and multiple sources of rock breaking equipment, aiming to improve the efficiency of heading and mining. Lastly, the intelligent collaborative control technology needs to break through traditional system structures and develop relevant intelligent control systems suitable for specific locations.

Besides the aforementioned technology, there are other technologies such as automatic cutting technology, driving navigation and positioning technology, intelligent support technology and robot technology [36,37]. These technologies represent the future development trend in intelligent mining and heading and will significantly transform and enhance the mining industry by providing robust support and ensuring sustainable development.

3.2 Mining and heading equipment

Underground rock excavation is an interaction process between rock breakage machine and rock mass. The mining and heading equipment influences the rock breakage efficiency and then determines the developed level of mining and heading technology. In terms of mining and heading equipment, the mining and heading technology has developed from manpower or animal power, manual drilling and blasting, fully mechanized mining and heading or fully automatic rock drilling jumbo to intelligent and unmanned mining and heading in coal and metal mines, as shown in Fig. 5. In this work, drilling rig, bolter miner used in coal mining, as well as boom-type roadheader, tunnel boring machine (TBM) and shaft boring

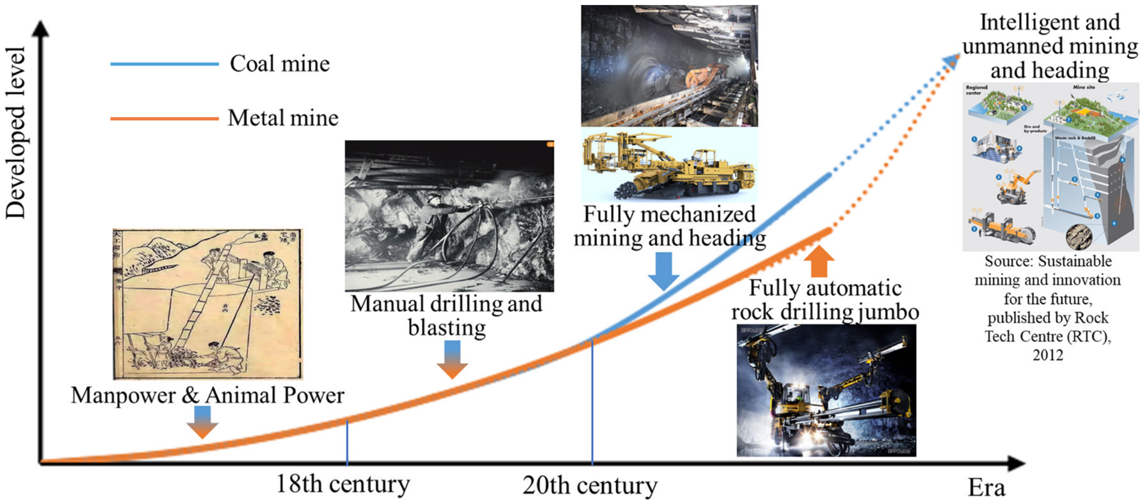


Fig. 5 Developed levels of mining and heading technology in coal and metal mines

machine used in hard rock mining at the same time are mainly introduced. At present, the main manufacturers of mining equipment are Sandvik, Komatsu, Joy globe (Komatsu), Atlas Copco, Epiroc, Robbins and CAT. With the rapid development of the manufacturing industry, a number of manufacturing enterprises in China have also emerged, such as CREG, NHI, CRCC, SANY, and TALEN Coal Mine Machinery.

(1) Drilling rig

Drilling rig is an important part of intelligent mining construction. At present, coal mine underground drilling rigs have achieved great development, from a single split structure to a variety of models such as crawler, rubber wheel and automatic drilling rig [17]. Since the 1980s, relevant research institutes have carried out a lot of effective research on coal mine underground drilling technology and equipment. To date, more than 60 types of full hydraulic split and crawler drilling rigs have been formed in China, including ZDY, ZYW, CMS and other branded series [38], which has basically met needs of different roadway conditions, construction strata, construction hole depth and drilling types. As shown in Fig. 6, the ZDY series drilling rigs developed by Xi'an Research Institute (China) have a torque range of 120−20000 N·m, a power range of 7.5−242 kW, and a maximum drilling capacity of more than 2000 m.

(2) Bolter miner

In order to increase the speed of excavation and enable parallel operation of anchors under single entry driving, Voestalpine (Sandvik) developed the first anchor digger (ABM20) in 1991. Several sets of jumbolter and temporary support are installed on the main frame, and the cutting mechanism with the same width as the roadway is installed on the auxiliary frame. The ore and rock are cut by the relative sliding of the main and auxiliary frames, so that the parallel operation of the driving and anchor is realized. After 30 years of development, it has a mining height of 1.2−5.5 m, cutting width of 4.0−7.2 m, cutting power of 200−340 kW, the whole machine mass 60−115 t, and more than 30 types, adapt to different working conditions of a full series of bolter miners [39]. Typical bolter miners are shown in Fig. 7. In addition, according to different surrounding rock conditions and supporting parameters, excavation equipment can be integrated to form a complete set of rapid heading equipment system with cutting, loading and supporting functions (Fig. 8).

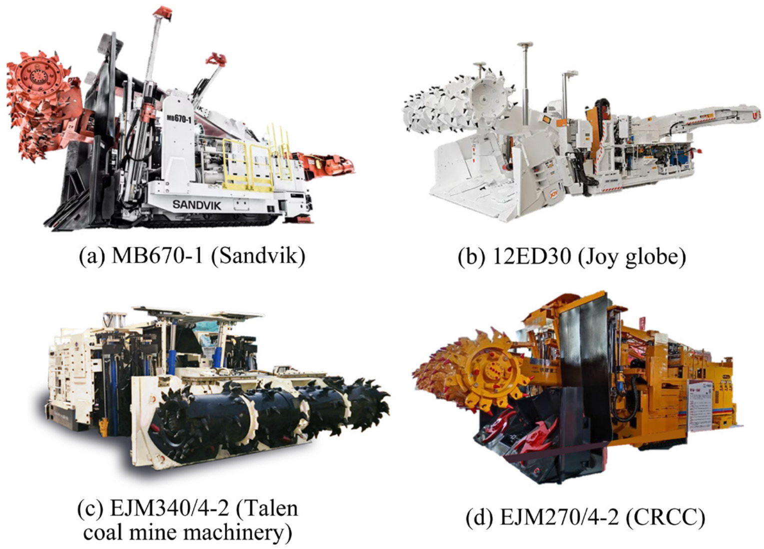
(3) Boom-type roadheader

The boom-type roadheader is mining and tunneling equipment that commonly uses conical picks as rock breaking tools. It has the advantages of small size, flexible operation, low rock disturbance and high mechanization [40]. It can excavate any section shape and is widely used in tunnels for mines, railways, highways, subways, water conservancy projects, and other tunnel excavations [41]. With the development of technology, the boom type roadheader is continuously improved and enhanced in automation, intelligence and multifunctionality. For example, Sandvik has developed the MH621 heavy-duty hard rock heading machine (Fig. 9(a)), powered by

(a) ZDY3200S split drilling rig (b) ZDY6000L drilling rig with crawler

(c) ZDY3500JD directional drilling rig with rubber wheel (d) ZDY2500LDK automatic directional drilling rig

Fig. 6 Drilling rigs of Xi'an Research Institute (China)



(a) MB670-1 (Sandvik) (b) 12ED30 (Joy globe)

(c) EJM340/4-2 (Talen coal mine machinery) (d) EJM270/4-2 (CRCC)

Fig. 7 Typical bolter miners

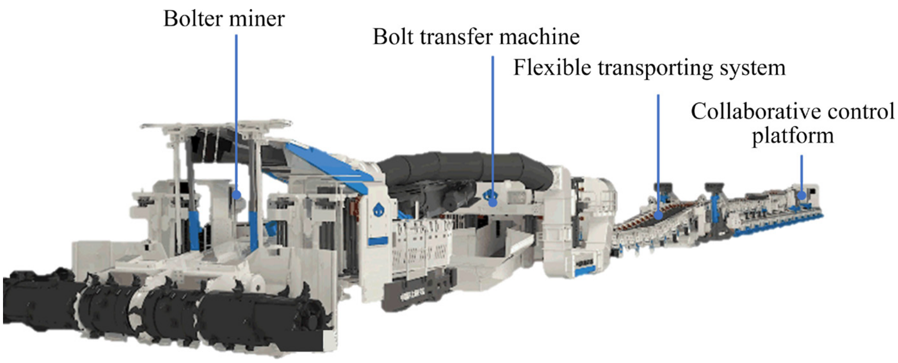


Fig. 8 Intelligent equipment system for rapid driving (Coal Sea Dragon)

electric power, which performs well in rock excavation with a uniaxial compressive strength of 100 MPa by installing a transverse axis cutting head on the telescopic boom. The machine can replace different cutting heads according to different rock conditions and has strong geological adaptability. SANY has developed the EBZ318H heading machine specifically for the hard rock excavation (Fig. 9(b)), which uses a longitudinal axis cutting head with a cutting power of over 300 kW.

(4) Tunnel boring machine (TBM)

Underground tunnel boring machine (TBM) construction is one of the important means to meet the intensive, automated and intelligent development

(a) MH621 (Sandvik) (b) EBZ318H (SANY)

Fig. 9 Typical boom-type roadheader

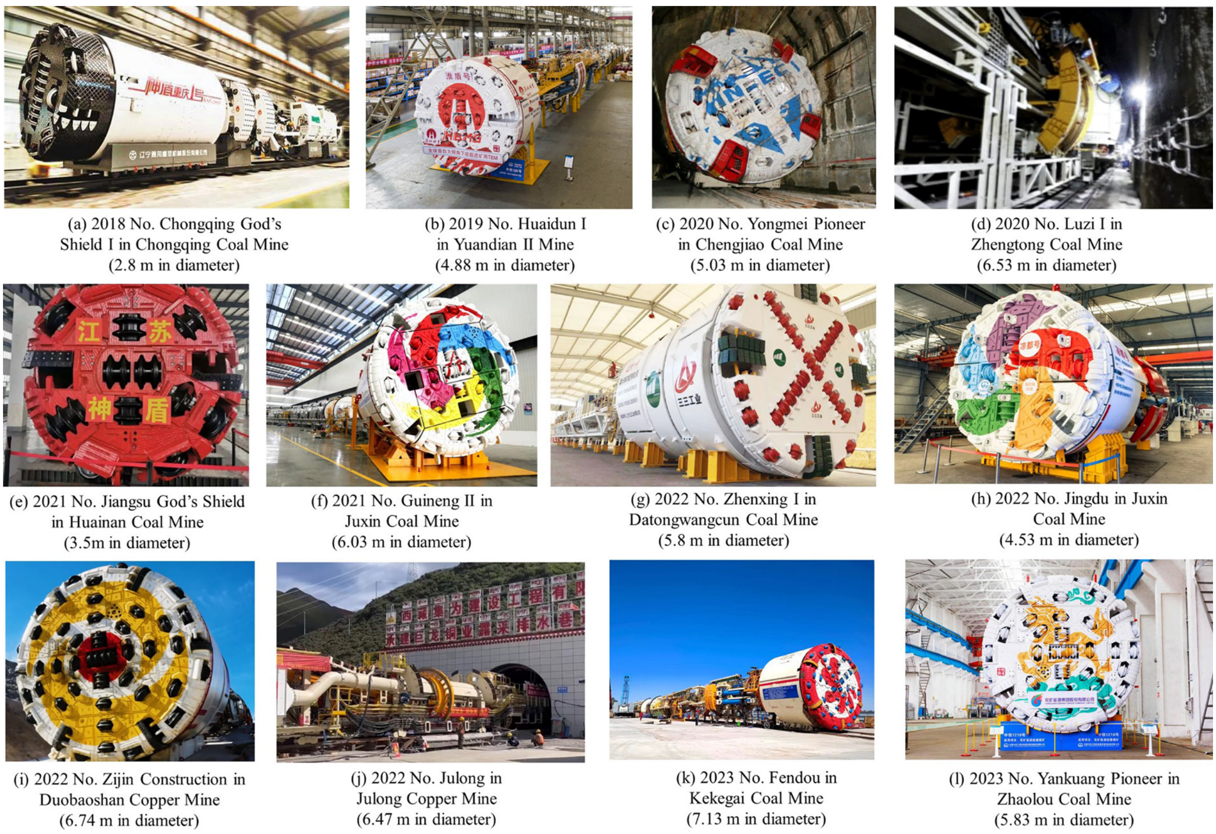
and efficient construction production of large-scale deep excavation with high rock strength. According to incomplete statistics, there are currently more than 100 TBMs in more than 60 mines worldwide, with excavating projects covering more than 220 km [42]. Through structural optimization, the overall length of mining TBMs has been reduced from the conventional 300 m to approximately 60 m. According to statistical analysis of usage, the speed of TBM excavation can reach 3−10 times that of drilling and blasting methods, and 2 8 times that of the comprehensive excavation method [43]. Figure 10 shows some mining TBMs in China, including the fully functional and intelligent TBM ‘No. Yongmei Pioneer’, the ‘No. Guineng II’ TBM that achieves ultra-small turning radius in the engineering applications, the inclined open-type TBM ‘No. Fendou’ and the ‘No. Huaidun’ TBM used for excavation in steep downhill slopes in coal mine and ‘No. Zijin’ and ‘No. Julong’ in copper mine.

(5) Shaft boring machine

Shaft boring machine is expected to overcome the technical deficiencies of traditional drilling and blasting methods and is a crucial support for achieving intelligent construction of kilometer-level shafts. Starting from the 1960s, representative full-section and partial-section shaft boring machines were developed by Robbins in the United States and Herrenknecht in Germany, and successfully applied in engineering practice. In recent years, companies in China have also started to upgrade and transform shaft boring machines, and have innovatively developed guided-core vertical shaft boring machines, mechanical/ fluidized upward slag discharging full-section hard rock vertical shaft boring machines, self-propelled raise-boring machines, and others (Fig. 11) [44].

(6) Other mining and heading equipment

In addition to several commonly-used mining equipments mentioned above, Komatsu has developed the MC51 continuous mining equipment



(a) 2018 No. Chongqing God's Shield I in Chongqing Coal Mine (2.8 m in diameter)
(b) 2019 No. Huaidun I in Yuandian II Mine (4.88 m in diameter)
(c) 2020 No. Yongmei Pioneer in Chengjiao Coal Mine (5.03 m in diameter)
(d) 2020 No. Luzi I in Zhengtong Coal Mine (6.53 m in diameter)
(e) 2021 No. Jiangsu God's Shield in Huainan Coal Mine (3.5m in diameter)
(f) 2021 No. Guineng II in Juxin Coal Mine (6.03 m in diameter)
(g) 2022 No. Zhenxing I in Datongwangcun Coal Mine (5.8 m in diameter)
(h) 2022 No. Jingdu in Juxin Coal Mine (4.53 m in diameter)
(i) 2022 No. Zijin Construction in Duobaoshan Copper Mine (6.74 m in diameter)
(j) 2022 No. Julong in Julong Copper Mine (6.47 m in diameter)
(k) 2023 No. Fendou in Kekegai Coal Mine (7.13 m in diameter)
(l) 2023 No. Yankuang Pioneer in Zhaolou Coal Mine (5.83 m in diameter)

Fig. 10 TBMs for tunnelling in mine in China based on the oscillating disc cutting technology (Fig. 12(a)). It can cut rocks with a maximum uniaxial compressive strength of 250 MPa. Sandvik's Reef Miner MN220 is a disc cutting mechanical equipment used for mining (Fig. 12(b)). It uses disc undercutting technology to overcome the tensile strength of rocks and achieve rock fragmentation, resulting in lower cutting energy consumption and higher efficiency. Additionally, there are TM-100 (Fig. 12(c)) hard rock mining equipment developed by Mitsui Miike Manufacturing in Japan, and the Mobile Miner 40 V (Fig. 12(d)) hard rock mining equipment developed by Epiroc in Sweden. Both of these devices can cut rocks with a strength of up to 220 MPa.

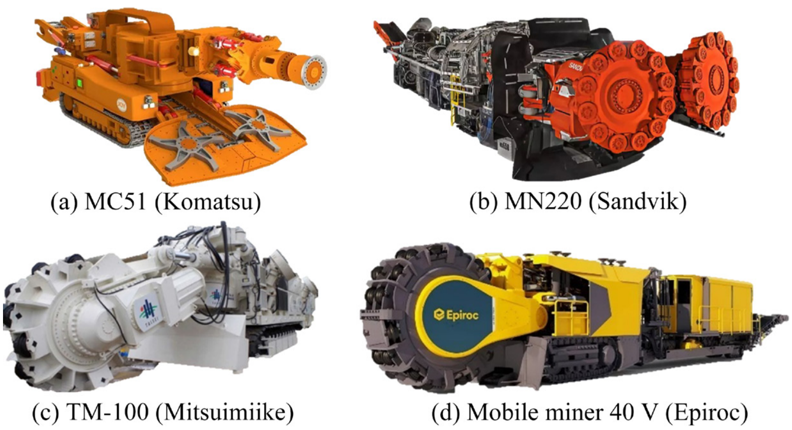
4 Process of non-explosive mechanized and intelligent mining and heading

Based on the innovation of mining technology and the development of mechanical equipment, it is necessary to develop new non-explosive mechanical and intelligent mining and heading processes. The specific steps including in-situ monitoring, cuttability improvement, intelligent control and performance evaluation are shown in Fig. 13.

(a) MSJ5.8/1000/1.6D (b) SBM/1000 (c) No. Shouchuang

(d) No. Mengxiang (e) CY-R80V/CY-R120V

Fig. 11 Shaft boring machines in China



(a) MC51 (Komatsu) (b) MN220 (Sandvik)

(c) TM-100 (Mitsuimiike) (d) Mobile miner 40 V (Epiroc)

Fig. 12 New mining and heading equipment

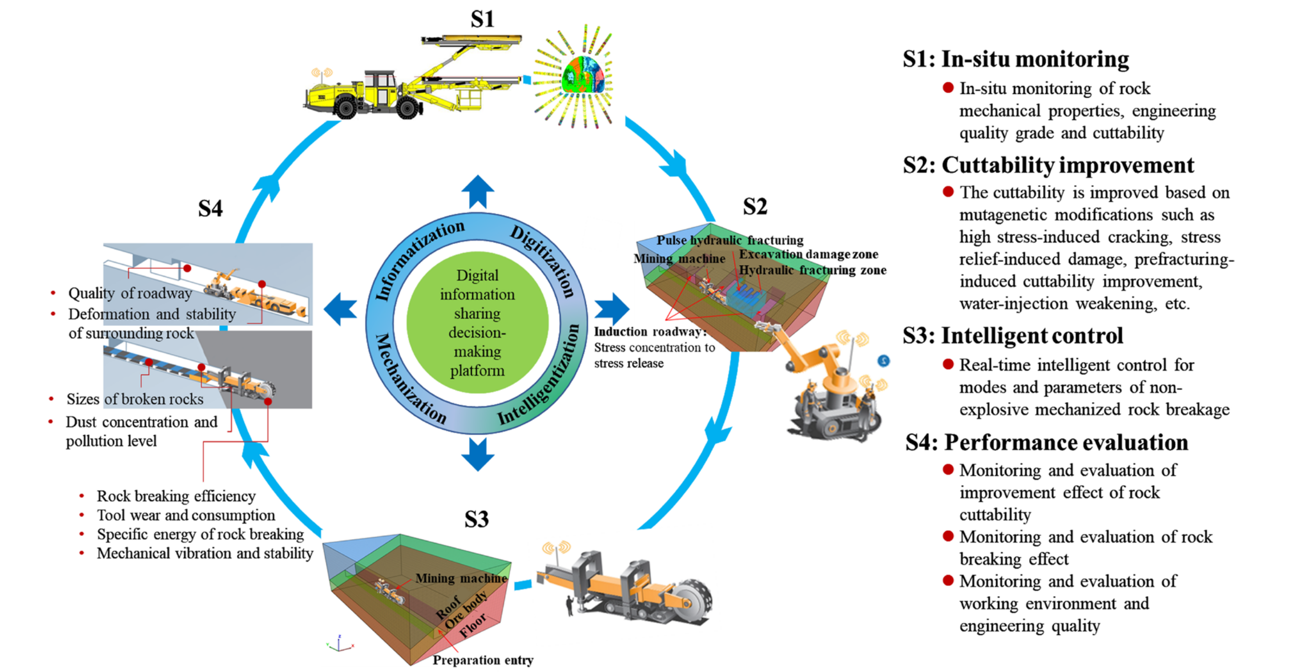


Fig. 13 Non-explosive mechanized intelligent mining process

Step S1: During the drilling process of the drilling rig in the deep hard rock, the drilling parameters are collected and analyzed through sensors to obtain the mechanical characteristics of the rock mass, which is called as MWD technology. Combined with in-situ acquisition techniques for collecting stress parameters and structural characteristics of the rock mass under different geological conditions, a characterization model is constructed to perceive and comprehensively evaluate the mechanical properties, engineering quality, drillability and cuttability of the rock mass. Based on the evaluation results, a full-information digital twins model of ore rock is established by integrating digital image processing, computer vision, deep learning and other technologies. The model information is synchronized by the whole-process monitoring and evaluation technology. The model is divided into a mining geological model and a mining engineering model. The mining geological model is used to intuitively obtain ore body data, while the mining engineering model facilitates the grasp of mining engineering data by the staff.

Step S2: Based on the full-information model, the locations of ore bodies with high engineering quality are determined, and in-situ induced mutation modification measures are implemented. Firstly, the stress release and damage zones in orebody are induced and formed by excavating induction roadway. If the damage zone still does not meet the requirements, artificial defects are created by pre-drilling holes or pre-cutting grooves, or high-pressure pulse water jets are injected for producing rock fracturing, creating free surfaces and supplementary spaces and then improving the cuttability of hard rock.

Step S3: For orebody with cuttability improvement, non-explosive mechanized rock breakage is conducted. According to the orebody properties, the rock breaking mechanized equipment can be selected, and the rock breaking parameters of equipment (e.g., tool size, tool spacing, cutting angle, cutting depth, cutting speed, and cutting path) can be automatically controlled and optimized for self-adaption with orebody properties.

Step S4: Real-time monitoring is conducted on the rock breaking performance, operating environment, machine behaviour and operation parameters to evaluate the effectiveness of cuttability improvement and the geomechanical properties of rock mass, which is called as the monitoring while mining or heading (MWM or MWH) technology. Evaluation indicators include rock breaking specific energy, tool wear and consumption, rock-breaking efficiency, machine vibration and stability, broken ore size, dust concentration and pollution level, drift quality, surrounding rock deformation, etc. The monitoring data and evaluation results are fed back to the mining geological model and the mining engineering model for real-time updating of the model information. Based on the intelligent collaborative control technology, the S1−S4 steps are self-organized in a cyclical manner until the safe and efficient mining of deep hard rock orebody is achieved.

Development of non-explosive mechanized intelligent mining and heading process (Fig. 13) can realize in-situ monitoring, perception and comprehensive evaluation of the mechanical properties and cuttability of the rock mass, cuttability improvement of hard-to-cut rock, real-time control for modes and parameters of mechanized rock-breaking, and monitoring and evaluation of the overall performance of mining and heading operations. Through the coordination and connection of the above process on a digital information sharing and decision-making platform based on the Internet of Things technology, the mechanized, informatized, digitalized and intelligentized mining can be achieved.

5 Management of non-explosive mechanized and intelligent mining and heading

For achieving safe and efficient non-explosive mechanized mining and heading, a process management model based on the PDCA cycle was proposed, as shown in Fig. 14. The cycle includes the following four steps: formulation of mining and heading plan (Plan), mining and heading operation (Do), monitoring and evaluation of operation performance (Check) and adjustment of plan (Adjust). The plan step is taken to make the mining and heading parameter design based on the in-situ

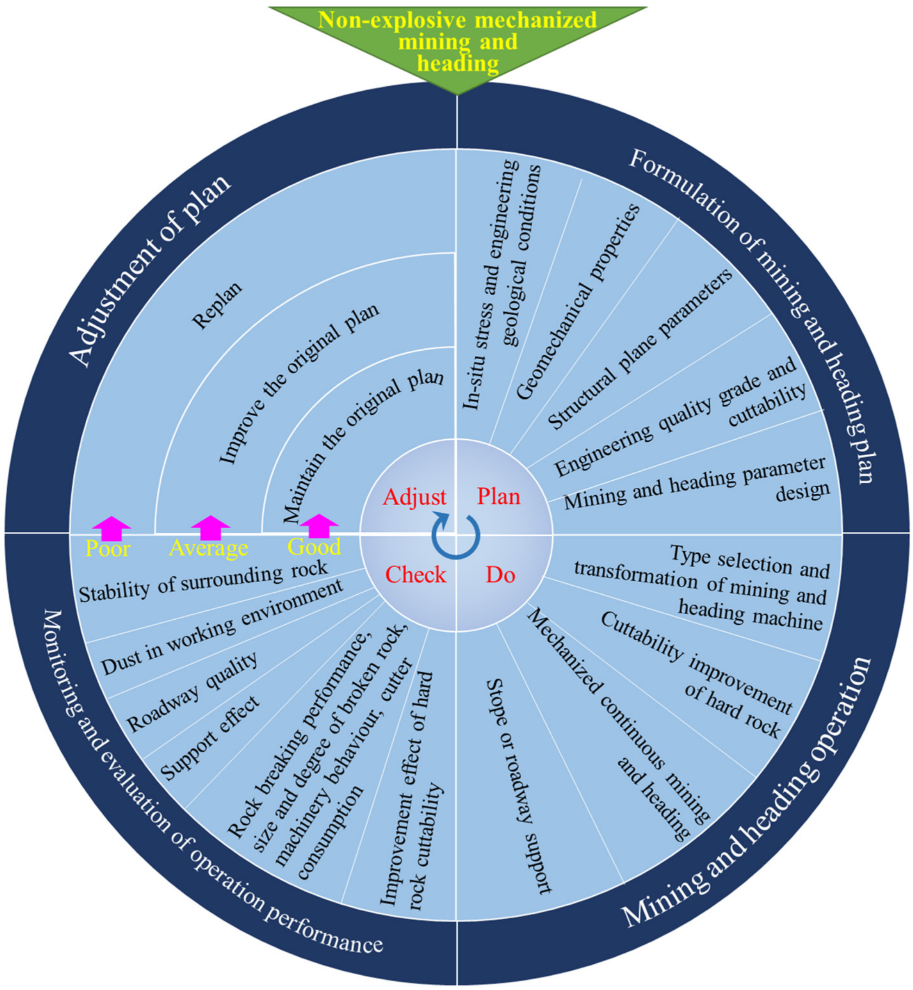


Fig. 14 PDCA cycle management model for non-explosive mechanized mining and heading

stress and engineering geological conditions, geomechanical properties of rock, structural parameters of rock, engineering quality grade and cuttability of rock. The operation process implements the type selection and transformation of mining and heading machine, cuttability improvement of hard rock, mechanized continuous mining and heading, and stope or roadway support. The checking step is conducted to monitor and evaluate the operation performance for understanding the improvement effect of hard rock cuttability, rock breaking performance, size of broken rock blocks, machinery behaviour, cutter consumption, support effect, roadway quality, dust concentration, and surrounding rock stability. The adjustment of plan selects the procedure to replan, improve or maintain the original plan, according to the checked results.

The specific management cycle can be divided into three key themes: deep high in-situ stress induced utilization and energy regulation with considering beneficial utilization of environmental factors, mutagenesis modification for risk reduction and cuttability improvement of the hard rock transformed from hardness to softness, and multi-source rock breakage combined with mechanical cutters, hydraulic, thermal approaches from innovation and diversification of rock breakage methods (Fig. 15). Correspondingly, there are three subgrade PDCA cycles. For the aforementioned three key themes, the formulations of plans are taken to design the induction engineering, mutagenic modification and rock breaking process, respectively, based on the stress and geological conditions, geomechanical properties, structural plane parameters, engineering quality grade and

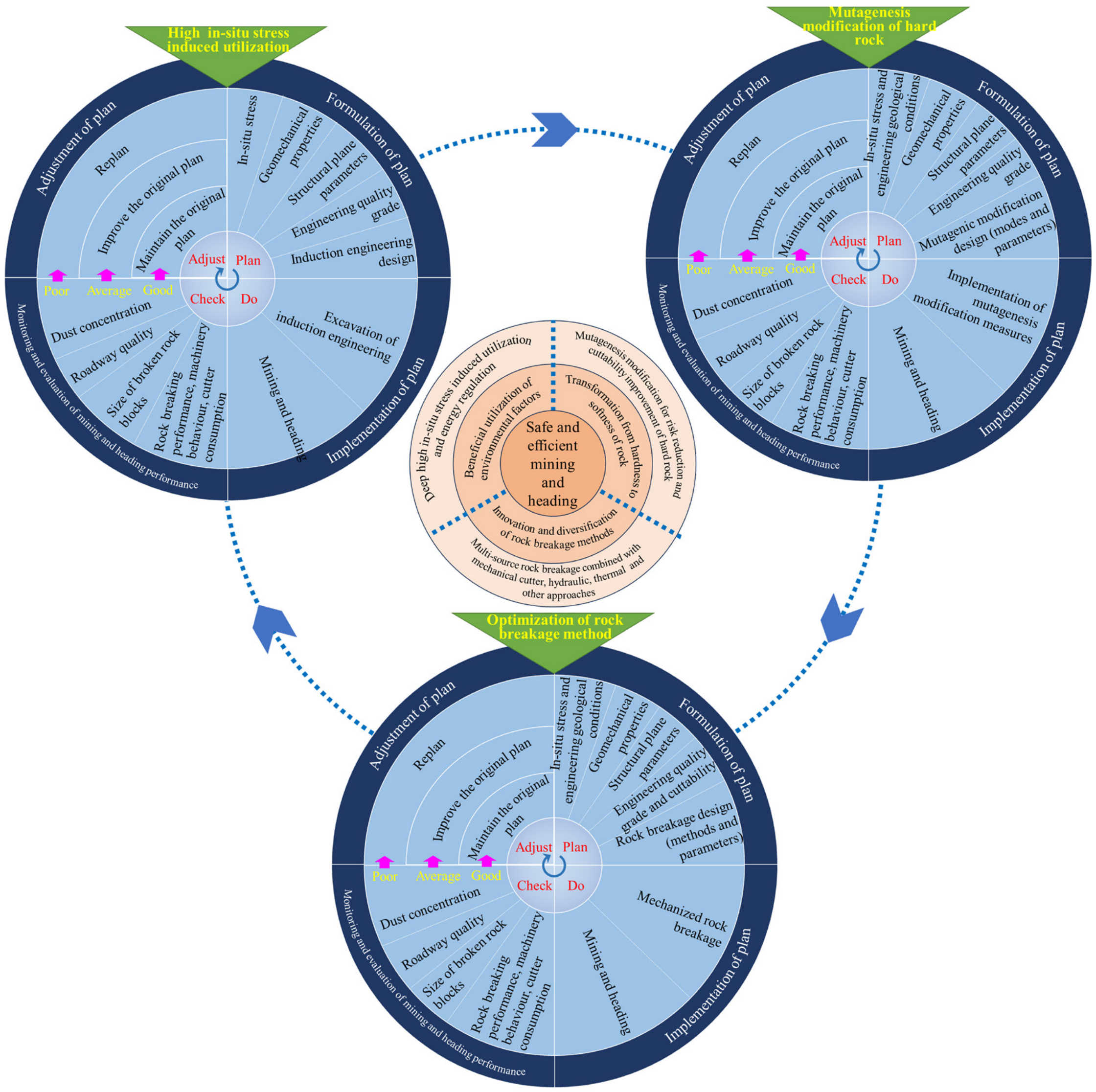


Fig. 15 Management model for safe and efficient non-explosive mechanized mining and heading

cuttability of rock. The induction engineering includes induction engineering forms and excavation parameters, selected from roadway for stress relief, pre-drilling hole, pre-slitting groove, etc. The mutagenic modification methods include the modification modes and the associated parameters, selected from high pressure water injection, pulse hydraulic fracturing, explosive or liquid CO_2 micro-blasting, pre-fracturing with hydraulic jacks in hole, etc. Rock breaking methods can be selected from mechanical cutters (cutting, impact, coupled cutting and impact by the point-attack pick, impact tip and rolling cutter), high pressure water jet, ultra-high speed bullet impact, heat impact (high temperature flame, microwave heating, laser irradiation, plasma, and liquid nitrogen jet), ultrasonic wave, etc. The implementations of plans are conducted to take the excavation of induction engineering, mutagenesis modification measures and mechanized rock breakage, respectively, and to operate the mining and heading. Hereafter, the performance of mining and heading is monitored and evaluated. Finally, the mining and heading plan is adjusted according to the evaluation results. Through the above PDCA cycle managements, the safe and efficient mining and heading can be achieved.

6 Conclusions

(1) The connotation of non-explosive mechanized and intelligent mining and heading was divided into smart perception, wise decision and intelligent control. In addition, the evolution framework was proposed by considering the aspects of technology, equipment, process and management. Particularly, the development of technology and equipment has been summarized to be more multi-functional, automatic, intelligent and suitable for mining and heading in hard rock. In response to the demands and challenges of deep mining, it is urgent to develop technologies such as in-situ geological condition acquisition, parallel excavation and support, non-explosive mechanized mining, whole process monitoring and evaluation, and intelligent collaborative control with big data.

(2) The process of non-explosive mechanized and intelligent mining and heading was depicted, which included four steps: in-situ monitoring, cuttability improvement, intelligent control and performance evaluation to achieve mechanization, information, digitization and intelligentization of the rock excavation.

(3) The PDCA cycle was established to manage the process of non-explosive mechanized and intelligent mining and heading, and three subgrade PDCA cycles were further established to manage the processes of deep in-situ stress induced utilization and energy regulation, mutagenesis modification for risk reduction and cuttability improvement of hard rock, and multi-source rock breakage. Through the above PDCA cycle managements, the safe and efficient mining and heading in underground mine can be achieved.

CRediT authorship contribution statement

Shao-feng WANG: Conceptualization, Funding acquisition, Methodology, Data curation, Validation, Supervision, Writing – Review & editing; **Yu-meng WU:** Writing – Original draft, Data curation, Investigation; **Xin-lei SHI**: Data curation, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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地下矿山非爆机械化智能采掘

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摘　要：非爆机械化采掘是替代传统钻爆法进行深部硬岩开挖的一种新方法，其智能化升级包括智能感知、智能决策和智能控制。在综合分析岩石采掘工程涉及的两大问题(破碎和稳定)和三大要素(环境条件、岩体特性、采掘参数)的基础上，建立包括岩体及环境特性原位监测、硬岩可切割性改善、采掘参数智能控制和采掘表现性能评价在内的非爆机械化智能采掘工艺，以实现岩石采掘装备的机械化、自动化、无人化，采掘工艺的连续化、精细化、协同化，以及采掘管理的信息化、数字化、智能化。此外，建立非爆机械化智能采掘 PDCA 循环管理模式，通过深部高应力诱导利用和能量调控、硬岩诱变改性降危增割和多源载荷联合破岩 3 个子循环的协同，实现地下矿山安全高效采掘。

关键词：深部开采；非爆机械化开挖；智能采掘；采掘工艺；管理模式

(Edited by Bing YANG)