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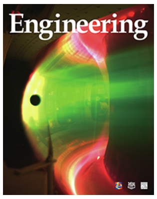

Views & Comments

Key Engineering Technologies to Achieve Green, Intelligent, and Sustainable Development of Deep Metal Mines in China

Meifeng Cai [a,b], Peng Li [a,b], Wenhui Tan [a,b], Fenhua Ren [a,b]

[a] *School of Civil and Resources Engineering, University of Science and Technology Beijing, Beijing 100083, China*
[b] *Key Laboratory of Efficient Mining and the Safety of Metal Mines (Ministry of Education of the People's Republic of China), University of Science and Technology Beijing, Beijing 100083, China*

1. Introduction

Metal mineral resources are the most important industrial raw materials in the world and play an indispensable role in the development of the national economy, social and material civilization, and scientific and technological progress. After decades of sustained and high-intensity development, shallow metal mineral resources in China have gradually decreased and are nearly exhausted [1]; thus, the exploitation of metal mineral resources is comprehensively advancing toward greater depths. At present, more than 20 underground metal mines have reached or exceeded a mining depth of 1000 m [2]. According to statistics, the mining depth of more than one-third of China's underground metal mines will exceed 1000 m over the next decade, and the maximum mining depth will range from 2000 to 3000 m. It has been predicted that, with the advancement of exploration technology and the increase in exploration depth, it is entirely possible to encounter several large metal deposits at depths ranging from 3000 to 5000 m in China. Consequently, deep mining is the most urgent problem facing the development of metal mines in China, while remaining the most important way to ensure the sustainable development and supply of metal mineral resources in the future. Against this background, we propose key engineering technologies to address the problems presented by deep mining from a strategic perspective.

2. Major problems in deep mining

Safe and efficient deep mining presents a series of engineering challenges [3–5]. Major problems in deep mining largely originate from the following aspects:

(1) High *in situ* stress. Under high-stress conditions, mining excavation involves destructive ground pressure activities; these can result in mining dynamic disasters [6] such as rockburst, wall collapse, roof fall, and water inrush, which may seriously affect production safety and normal operations.

(2) Lithology deterioration. At great depths, the structure and mechanical properties of rock masses vary greatly, which greatly burdens the support, affects subsequent mining safety, and seriously affects the mining efficiency and economic benefits.

(3) A high-temperature environment. The high-temperature environment in deep mines can greatly degrade the mechanical properties of the surrounding rocks and severely affect the safe operation of equipment, production efficiency, and worker health, which can cause unpredictable disasters and accidents.

(4) Deep hoisting. With increasing mining depth, the hoisting height of ore and various materials increases notably, resulting in major increases in the difficulty and cost of hoisting. The use of traditional rope-hoisting techniques not only presents difficulties in meeting the requirements of deep hoisting, but also potentially threatens production safety.

3. Key engineering technologies in deep mining

3.1. Rockburst prediction and prevention and control technology

A rockburst is a dynamic hazard induced by mining excavations, and is the primary type of disaster in mining engineering. Rockburst prediction is a world-class, high-difficulty problem. The first task in mine safety maintenance is to understand and control rockburst. Mining excavation disrupts the equilibrium state and generates disturbance energy in the surrounding rock. When the disturbance energy accumulates to a high level, it may be abruptly released when the surrounding rock is broken under high-stress application or along a weak plane in the rock mass, and rockburst may occur [7]. Based on this understanding of the rockburst mechanism, rockburst prediction should be closely combined with the mining process. Depending on future mining schemes, the magnitude of possible rockburst, its initiation time, the spatial distribution of the disturbance energy in the rock mass, and its variation trend throughout the mining process as induced by mining excavation should be quantitatively calculated via numerical modeling, mathematical statistics, and other analytical methods. Subsequently, the development trend and spatiotemporal strength regularity of future mining-induced rockburst can be quantitatively predicted based on knowledge of the relationship between seismic energy (i.e., released energy) and the magnitude of seismic activity in seismology [7]. Similarly, the prevention and control of rockburst should mainly start with optimizing the mining methods, layout, and excavation sequence; reducing high-stress

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concentration and large-displacement areas in the surrounding rock; and lowering and controlling the accumulation of disturbance energy in the rock mass during mining excavation. In this way, the occurrence of rockburst can be roughly controlled and avoided. Moreover, support measures that can absorb energy and prevent impact can be adopted to prevent and weaken the impact strength of rockburst.

3.2. Support technology

Common mining methods in underground metal mines are divided into three categories—namely, the open stope method, the caving method, and the filling method—depending on the methods of excavation and support. Among these, the filling method incurs the highest cost. An applicable method is decided for each mine, largely based on the ore value and difficulty of goaf maintenance. However, in order to realize green mining, control stratum movement, and minimize surface subsidence (especially in order to control severe ground pressure activity in deep mining), the filling method is the mining method that should be chosen for most mines, including iron mines. This suggests that a great reform will be necessary as the traditional mining mode is replaced by the filling method. Nevertheless, the principle of balancing mining benefits and support costs should be observed. In order for the filling method to be widely applied, it is necessary to reform the filling technology and materials and extensively reduce the filling cost. A filling technology that involves the application of solid waste from the mine is the most promising technical solution. The full-tailings paste-filling technology that has been developed in recent years can yield a high-quality filling body with a uniform paste strength and a high tight-filling ratio of goafs along with low cement consumption, which can effectively control ground pressure activities and stratum movement. This technique represents the future development trend of filling technology. In addition, cementitious materials account for a large proportion of the paste-filling costs. The development of new filling materials with ultrafine properties, high strength, a low price, and rapid hardening can effectively reduce the filling cost.

3.3. High-temperature environment control and cooling technology

Common deep mine cooling technologies that are used worldwide can be divided into two categories: non-artificial and artificial cooling technologies. Non-artificial cooling technology includes many methods, such as mine ventilation, heat-source isolation, the precooling of rock strata, and goaf filling; among these, mine ventilation is the most widely applied method. However, the drawbacks of mine ventilation include a high cost and low cooling capacity. Furthermore, it is difficult for conventional mine ventilation to meet the cooling requirements when serious mine heat hazards occur. Therefore, artificial cooling measures must be adopted simultaneously with mine ventilation. Artificial refrigeration cooling technology is currently widely implemented in metal mines, and mainly includes water cooling systems and ice cooling systems. A water cooling system produces cold water through a refrigerating unit, and then uses a high–low-pressure heat exchanger and air cooler to cool the airflow input discharged from the ventilation system into the mine in order to further cool the working face. This system actually applies air-conditioning technology in underground mines. An ice cooling system transports granular ice or muddy ice prepared by an ice-making machine on the surface to an underground ice-melting pool through wind or water power, sprays and melts the granular ice or muddy ice using the backwater of the working face, and then sends the cold water formed after the ice melts to the working face in order to reduce the working face temperature via air cooling or spray cooling. In general, both non-artificial and artificial refrigeration technologies are passive cooling measures. Engineering practice has shown that these two cooling technologies not only incur high costs, but also yield poor cooling effects in deep mines.

To efficiently solve the problem of cooling in deep mines, it is necessary to develop active cooling technology, which should focus on the following two aspects:

(1) Thermal insulation technology for high-temperature strata. The high-temperature environment in deep mines is mainly caused by the thermal radiation effect of high-temperature rock formations. Thus, it is necessary to develop new and efficient heat-insulation materials, technologies, and processes to isolate high-temperature heat sources in rock formations, based on artificial refrigeration and cooling technology, in order to achieve a significant cooling effect.

(2) Geothermal heat-recovery technology in deep mines. Geothermal heat is a kind of natural energy. The existing cooling technologies are passive measures that treat geothermal energy as a disaster to prevent. If heat-exchange technology is employed to recover the geothermal energy contained in rock formations during deep mining, thereby combining deep mining with deep geothermal heat recovery, the passive cooling cost can be greatly offset, thus creating a subversive, economical, and effective technical approach for deep mine cooling.

3.4. Hoisting technology

The hoisting operation is as important in the mining process as the rock drilling and excavation operations. Multi-rope friction or winding hoists are widely applied in metal mines. After entering the deep mining stage, steel wire ropes are continuously lengthened and thickened, which not only increases the lifting load and greatly reduces the effective lifting capacity, but also causes large tension fluctuations in the lifting wire rope due to the notable change in tail rope length, resulting in wire breakage. This has become the main factor restricting the safety of frictional lifting. According to global statistics, the single-stage maximum lifting heights of friction and winding hoists are only approximately 1800 and 3000 m, respectively. Multistage lifting must be adopted to achieve a larger lifting height, but this greatly increases the equipment cost while decreasing the lifting efficiency.

When the lifting height exceeds 3000 m, the heavy load, large inertia, and high torque caused by the steel wire ropes in rope-hoisting technology are unavoidable problems. Therefore, it is essential to develop cordless vertical-lifting technologies, such as linear motor-driven lifting technology and magnetic suspension-driven lifting technology. Cordless vertical-lifting technologies have the advantages of small equipment size, flexible movement, high efficiency, and no limit on the lifting height, and are suitable for lifting in deep mines. At present, the technology and equipment in this field are still at the preliminary, tentative stage; thus, further innovative research and scientific experiments are needed to develop practical technologies and products. It is suggested that China should focus on the research and development of these hoisting technologies and equipment in the future.

4. Green intelligent mining

The traditional mining modes and methods used in shallow mines are not suitable for deep mines, given the high stress, high temperature, notable changes in rock mass structure, and complex geological conditions of deep mines. To meet the requirements of green intelligent mining in deep metal mines and to improve the level of automatic and efficient mining, existing mining modes and techniques must be fundamentally adapted for use in deep mines.

4.1. Precision-cutting mining

In mining excavation, the traditional rock-breaking method involves drilling and blasting technology. However, blasting destroys the stability of the surrounding rock and threatens the safety of the mining process. Moreover, this method simultaneously collects ore and waste rock, which greatly increases the amount of waste rock being lifted in the mine and the workload of mineral processing. To improve the automaticity, precision, and efficiency of the mining process in deep mines, precise-cutting mining methods should be studied.

4.1.1. Mechanical continuous-cutting tunneling and mining technology

With the use of mechanical tunneling and mechanical rock drilling, continuous-cutting equipment has replaced traditional blasting mining technology in deep mining. The stability of the surrounding rock is greatly improved without blasting in the cutting space. Mechanical cutting can accurately mine the target ore and minimize the mining loss rate and ore dilution rate, thereby greatly reducing the lifting workload and number of support operations. Cutting, ore dropping, loading, and transportation are carried out in parallel and continuously, which is beneficial for realizing continuous mining, improving the mining efficiency, and ensuring safe mining. The operation of mining machines is restricted by the variability in metal deposits and complex geological conditions, as well as by the life and cost of the cutting head; these are the key frontier issues that should be solved in order to implement this technology.

4.1.2. High-pressure water-jet rock-breaking tunneling and mining technology

High-pressure water-jet technology is a cleaning and cutting technology that was developed in the 1970s. The high-speed water jet emitted from the high-pressure nozzle contains a great deal of energy and can produce a very high impact force on the target, which can be used to cut and break rocks. During high-pressure water-jet crushing and cutting, the produced waste can be automatically discharged, and water can be recycled through the simple physical purification of the used water. At present, rock breaking involving a high-pressure water jet has been realized in soft-rock and medium-hard rock engineering and is widely implemented in coal mines. However, when crushing hard rock, problems such as an insufficient water-jet pressure still remain; therefore, its application in metal mines is limited. To solve the problem of hard rock breaking, high-pressure water-jet technology should evolve toward ultrahigh pressure and high power. Hence, it is necessary to further develop and improve ultrahigh-pressure water-jet components and equipment, such as ultrahigh-pressure pumps, rotary seals, wear-resistant nozzles, and high-pressure pipe fittings, in order to create beneficial conditions for their application in hard rock metal-mine environments.

4.1.3. Laser rock-breaking tunneling and mining technology

Laser rock breaking applies heat generated by a high-energy laser beam to heat local rock rapidly. When the temperature is high enough, a series of complex physical and chemical reactions occur, and three rock-breaking forms—namely, breaking, melting, and vaporizing—are realized in succession with increasing rock temperature. In mining, only the rock must be broken. When a high-energy laser acts on the rock surface, the rock is locally heated and rapidly expands, thus increasing the local thermal stress. Once the thermal stress is higher than the ultimate strength of the rock, the rock is thermally broken, and rock cutting and breaking is realized [8]. In addition, the microcracks and pores on the rock surface reduce the ultimate strength of the rock, which intensifies the thermal cutting and breaking action.

4.1.4. Plasma rock-breaking tunneling and mining technology

When using plasma to break rock, it is necessary to first drill a hole into the rock mass, fill the front end of the hole with an electrolyte, and then tightly fit a coaxial blasting electrode into the hole. An energy-storage capacitor bank is connected to the coaxial blasting electrode via a detonating trigger, and the electrolyte is quickly converted into high-temperature and high-pressure plasma gas under the action of a large amount of electric energy. The high-temperature and high-pressure plasma gas rapidly expands to form a powerful shock wave, producing a blasting effect similar to that produced by chemical explosives [9]. The resulting pressure can exceed 2 GPa, which is high enough to break hard rock. Implementation of this technology has the potential to greatly improve the working environment and reduce the impact and damage of traditional blasting on surrounding rocks and the environment.

4.2. Wasteless mining

The goal of wasteless mining is to minimize the output and discharge of waste materials, improve the comprehensive utilization rate of resources, and reduce or eliminate the ecological and environmental damage caused by the exploitation of mineral resources. The wasteless mining mode considers the industrial ecology; it places mining activities at the center and links the mine ecological environment, resource environment, and economic environment into an organic industrial system in order to obtain the maximum amount of resources and economic benefits with minimum emissions. After the mining activity has ended, the mine environment and the ecological environment are integrated through minimal end treatment. To realize wasteless mining, it is necessary to vigorously improve the technical level of mining and beneficiation, reduce the ore dilution rate, minimize the waste output, and control the waste rock output rate from the source. Moreover, as much as possible, the recovery rate of mineral processing should be improved, the tailings discharge level should be reduced, and the amount of unusable ore resources components should be minimized by means of the high-level treatment of mineral processing and metallurgy. In addition, comprehensive recovery should be strengthened, waste recycling should be realized, the overall waste-utilization level should be improved, and zero emission and zero solid mine waste storage should be achieved.

4.3. Solution mining

Solution mining—a technique that integrates mining, beneficiation, and metallurgy—can be divided into three categories: *in situ* drilling solution leaching, *in situ* crushing solution leaching, and heap leaching. This technology directly recovers metal elements in the ore body through leaching liquid, which can greatly reduce the mining workload, decrease the need for mineral processing and smelting operations, lower the production costs, and provide a feasible method for deep low-grade ore recovery [10]. Compared with the traditional mining–beneficiation–smelting process, the cost of *in situ* solution mining can be more than 30% lower (even up to 50% lower), and thus provides an important application value for deep mining. In addition, *in situ* solution mining does not produce waste rock nor tailings, and it exerts no excavation disturbance nor influence on the ground environment. Thus, *in situ* solution mining is one of the main techniques for accomplishing green mining in the future. This mining technology is an interdisciplinary subject, and the current basic theory remains to be accomplished. Thus, further research is needed on granular seepage dynamics and the strong correlation mechanism among the multiple factors of the leaching process. In particular, there are too few kinds of bulk metals that can be recovered via this process at present, and only a few metal minerals—such as uranium, copper, and gold—can be effectively recovered. Therefore, extensive study is needed on the leaching process and recovery technologies for more metal minerals.

4.4. Integration of underground mining and mineral processing

Before the ore is lifted to the surface, preselection and preconcentration are performed underground so that most of the waste rock can be discarded; this can greatly reduce the lifting amount of ore and the discharge of waste rock on the surface. In deep mining, ore is crushed and ground into a slurry underground after preselection, and then hydraulically transported to a surface concentrator through pipelines. Compared with other transportation schemes, this technology yields a series of advantages, including low capital construction investment, strong adaptability to terrain conditions, and little or no land occupation. In addition, this technology facilitates environmental protection.

A concentrator is built underground, the mined ore is beneficiated underground, and a concentrate is then delivered directly to the surface, which can greatly reduce the amount of waste rock to be lifted and is an important way to solve the lifting problem. The waste rock and tailings that result from mineral processing remain in the mining room for goaf filling in order to realize *in situ* utilization and reduce the resultant pollution and damage to the ecological environment when waste rock and tailings are discharged on the surface. Moreover, there is no need to build mineral processing plants and tailings ponds on the surface, which lowers the cost of the land acquisition, construction, and management of tailings ponds, and eliminates the source of various natural disasters induced by tailings ponds. Therefore, the integration of underground mining and mineral processing is an important measure to give full play to the comprehensive benefits of the green and efficient development of mineral resources.

4.5. Intelligent unmanned mining

Intelligent unmanned mining is the best way to address the increasingly deteriorating deep mining and environmental conditions while maximizing the safety and efficiency of mineral resource development. Artificial intelligence is an important driving force in a new round of scientific and technological revolution and industrial transformation. Accelerating the integration of artificial intelligence and mining development engineering technology and realizing the intelligent unmanned mining of mineral resources comprise an important direction and forward-looking goal of mining development in the 21st century, as well as an important guarantee for the sustainable development and supply of metal mineral resources in China.

Overall, the construction of intelligent unmanned mines worldwide is still at a primary stage. At this stage, the core technology of intelligent unmanned mining still relies on the automation and intelligent control of traditional mining technology and production organization and management. Intelligent control is mainly realized via field or remote control. Progress in information and communication technology may promote the development of primary intelligent unmanned mining toward advanced intelligent unmanned mining, which would be characterized by the integration of advanced detection and monitoring systems, high-speed digital communication networks, the Internet, the Internet of Things, the fifth generation mobile communication technology, big data, cloud computing, and intelligent mining equipment and processes. The equipment and control system of unmanned mining in the advanced stage should possess the functions of intelligent target recognition and perception, independent memory, independent judgment, and independent decision-making. It should function similarly to an intelligent brain, without external remote control. The new generation of advanced unmanned mining technology will inevitably involve the transformation of mining technology and production processes. To realize the transition in unmanned mining from the primary stage to the advanced stage, it is absolutely necessary to fundamentally adjust the traditional mining mode, technology, process, and management means, which will include developing and innovating a series of subversive technologies and methods.

In recent years, a great deal of fruitful and innovative work targeting the research acceleration, popularization, and application of intelligent mining technology has been conducted in several mines in China, such as the Xingshan iron mine and the Sandaozhuang molybdenum mine, thereby achieving considerable progress and greatly narrowing China's gap with developed countries. However, at present, the equipment in certain small- and medium-sized metal mines in China remains relatively outdated, and advanced equipment must be imported at a high price, which restricts equipment upgrading and popularization, as well as the application of advanced mining technology. Therefore, the state and scientific research systems must increase their investments in science and technology in order to accomplish breakthroughs in automatic mining equipment and realize the localization of large-scale automatic equipment as soon as possible. This will create reliable conditions to accelerate the popularization and application of intelligent unmanned mining technology in China.

In summary, the mining industry is an industry that must be protected and developed due to its importance in the development of the national economy. As a developing country, China is at a critical stage in its period of rapid industrialization and urbanization. Therefore, the demand for metal mineral resources and metal mineral products will remain high for a certain period. The future development of mineral resources involves three major themes—namely, green mining, deep mining, and intelligent mining—among which deep mining is the overall theme. To solve a series of key technical problems presented by deep mining in the future, it is necessary to extensively absorb high-tech data from various disciplines and develop advanced and unconventional novel mining theories, technologies, and processes. On this basis, green intelligent mining modes should be established with higher efficiency, lower cost, minimal environmental pollution, and the highest possible safety conditions, and the output and production efficiency of metal mineral products should be enhanced, thereby ensuring the effective supply of mineral resources and the safe and sustainable development of the national economy of China.

5. Conclusions

In this article, we focused on the current status of and major problems in the deep mining of metal mineral resources in China. We proposed key engineering technological development strategies to address these problems, which include rockburst prediction, rockburst prevention and control, rock mass support, high-temperature environment control and cooling, and hoisting. In addition, we propose that the existing mining mode and technology must be fundamentally changed, with a focus on precision-cutting mining, wasteless mining, solution mining, the integration of underground mining and mineral processing, and intelligent unmanned mining, in order to meet the requirements of green intelligent mining in deep metal mines. The integration of forward-looking key innovative technologies in the abovementioned aspects will establish an innovative technological system for deep metal mines in China.

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