DOI: 10.3901/CJME.2016.0815.093, available online at www.springerlink.com; www.cjmenet.com

Development of Mining Technology and Equipment for Seafloor Massive Sulfide Deposits

LIU Shaojun[1, 2, 3], HU Jianhua[1, 2, 3, *], ZHANG Ruiqiang[1, 2], DAI Yu[1, 2, 3], and YANG Hengling[1, 2, 3]

1 *College of Mechanical and Electrical Engineering, Central South University, Changsha 410083, China*
2 *Shenzhen Research Institute, Central South University, Shenzhen 518000, China*
3 *State Key Laboratory of Deep Sea Mineral Resources Development and Utilization Technology, Changsha 410012, China*

Received June 21, 2016; revised July 19, 2016; accepted August 15, 2016;

Abstract: Seafloor massive sulfide(SMS) deposits which consist of Au, Ag, Cu, and other metal elements, have been a target of commercial mining in recent decades. The demand for established and reliable commercial mining system for SMS deposits is increasing within the marine mining industry. The current status and progress of mining technology and equipment for SMS deposits are introduced. First, the mining technology and other recent developments of SMS deposits are comprehensively explained and analyzed. The seafloor production tools manufactured by Nautilus Minerals and similar mining tools from Japan for SMS deposits are compared and discussed in turn. Second, SMS deposit mining technology research being conducted in China is described, and a new SMS deposits mining tool is designed according to the environmental requirement. Finally, some new trends of mining technology of SMS deposits are summarized and analyzed. All of these conclusions and results have reference value and guiding significance for the research of SMS deposit mining in China.

Keywords: deep sea mining equipment, mining key technology, seafloor massive sulfide deposits, new technology

1 Introduction

Seafloor massive sulfide(SMS) deposits, manganese nodules, and cobalt-rich crust are important parts of deep-sea mineral resources. With the increasing depletion of land resources and demand of mineral resources, SMS deposits will become an inevitable choice to satisfy the national strategic resource demands and facilitate human development in the future.

SMS deposits were discovered after manganese nodules and cobalt-rich crust, and have been attracting growing attention. SMS deposits are rich in Au, Ag, Cu, Pb, and other metal elements and are distributed at depth of 1.5 to 3 km on the seabed[1–2]. SMS deposits originate from a combination of submarine hydrothermal eruptions and cold water, thus the formation of the ore has a thickness of up to 10 m or more on the seafloor. The distributed form of the SMS deposits is shown in Fig. 1.

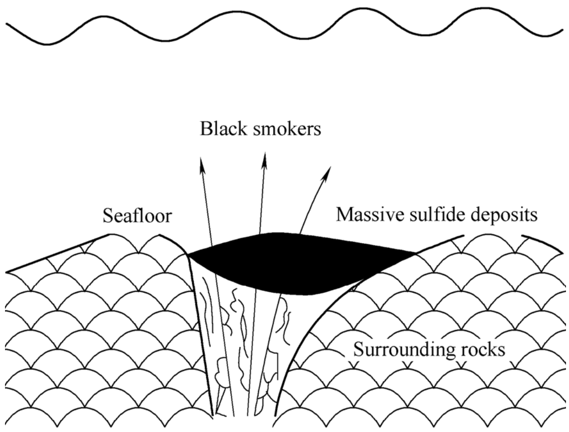

Fig. 1. Distributed form of SMS deposits

SMS deposits were first found on the west coast of Mexico and along the East Pacific Rise in 1979 and are abundantly deposited in the shallow waters. Later, it was confirmed that more than one hundred hydrothermal vents exist. These vents are mainly distributed in mid-ocean ridges, back-arc basins, and seamounts. Experts in the field believe that there are more than 1000 active sites on the seafloor[3]. Moreover, scientific evidence shows that there are more hydrothermal sulfide distributions in the vicinity of the active vents. Since the 1980 s, many survey activities have been concentrated in the southwest Pacific Ocean, and an increasing numbers of sites of SMS deposits were found around the Northern Mariana Islands, Fiji, Lau Basin, and

* Corresponding author. E-mail: hujianhua2008@hotmail.com
Supported by National Natural Science Foundation of China(Grant No. 51074179), National Hi-tech Research and Development Program of China (863 Program, Grant No. 2012AA091291), and Basic Research Foundation of Shenzhen Science and Technology Innovation, China(Grant No. JCYJ20150929102555935)

Okinawa Trough. So far, most of the SMS deposit potential mining areas are scattered. Due to its easy exploitation, highly commercial value, and low exploitation cost, a lot of money and resources are invested in this mineral source by many developed countries. Along with the progresses of the marine mining industry, further control of the marine environment makes mining SMS deposits possible in the shallow water that is more economical and environmentally friendly than land exploitation.

The Nautilus Minerals was approved by the government of Papua New Guinea(PNG) and given exploration licenses for exclusive economic zones(EEZs) for SMS deposits. The EEZ is shown in Fig. 2[4]. Neptune Minerals was also given corresponding exploration licenses. Since 2006, the technical preparation for commercial exploitation of SMS deposits was significantly strengthened by Nautilus Minerals in the southwest Pacific area. South Korea’s deep-sea mining consortium was approved by the governments of Fiji and Tanga to get the exploration licenses for the EEZs for SMS deposits, and a series of exploration activities were carried out by them. The international seabed areas of SMS deposits were distributed in the mid-ocean ridges, which are shown in Fig. 3[5]. The regional prospecting and exploration regulations of SMS deposits were approved by the International Seabed Authority in 2011. China, Russia, South Korea and France were approved and given approximately 10 000 km^2 of contract area for SMS deposit exploration. At the same time, the related mining systems and tools for SMS deposits were proposed and studied by their teams.

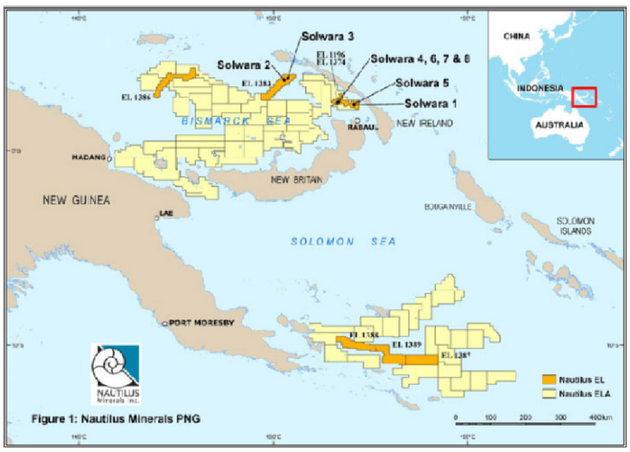

Fig. 2. Nautilus Minerals’ granted tenement licenses and explication in the EEZs of PNG

2 Technology and Recent Development of SMS Deposit Mining

2.1 Key technologies of mining SMS deposits

It is well know that the seabed poly-metallic nodules are laid on the soft seabed sediments; the nodules are several centimeters in diameter; and the cobalt-rich crusts are deposited on the surface of the substrates, which can be a few centimeters thick. Their storage characteristics are entirely different from that of SMS deposits. The terrains of the SMS deposit mines are rugged, and the thickness of SMS deposits is at least ten meters and can be up to tens of meters. Therefore, the SMS deposit seabed mining vehicle must include two functions: the first is cutting the SMS deposit rock and the second is stable movement in the rugged mining area.

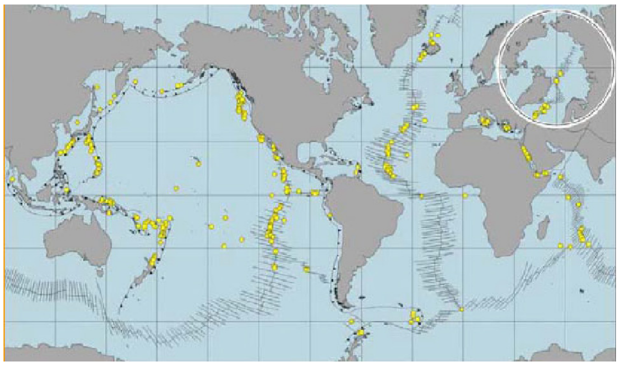

Fig. 3. Mid-ocean ridge and discoveries of poly-metallic sulfide deposits(yellow dots)

According to the mechanical properties of a large number of SMS deposit samples, the cutting characteristics of the SMS deposit are similar to that of coal, whereas, the toughness and plasticity are similar to that of salt and potassium carbonate. The axial compressive strength of the SMS deposit is less than 40 MPa. For cutting this type of rock, onshore coal mining technology is appropriate. For example, the spiral cutting head of the shearer used by Alpine Voest Company can be used to cut through thick rock layers up to 100 MPa in strength. In addition, the SMS sample was successfully cut in deep sea by Nautilus Minerals in 2008.

Seabed mining vehicles will need to be developed to be able to maneuver around the rugged mining area typical of SMS deposit mines. Taking into account the heavy load, low traveling speed and other requirements, the crawl type vehicle would be a feasible solution for a seabed mining vehicle. In the sea trials of poly-metallic nodule mining, scientists tested various forms of underwater mining vehicles and verified the crawl type’s feasibility. Currently, the crawler type has been successfully used on seafloor trenching machines and seafloor diamond mining vehicles. However, these vehicles operate on relatively flat sediments. SMS deposit mining vehicles are faced with different terrains and technical difficulties. The off-road vehicles are designed for complex terrains on land, such as the Swedish Bv206S tracked vehicles and Japan's articulated tracked vehicles, which could provide a model for SMS deposit mining vehicles[4]. But for submarine operations, obstacle recognition and obstacle avoidance, there are still many problems to be solved.

The density of the SMS deposit is similar to that of deep sea poly-metallic nodules. The technology and equipment of poly-metallic nodule mining can be used in deep sea SMS deposit mining. In spite of the wear of the pumps and other problems, the technical principle is comparable. As for mineral processing and smelting of the SMS deposit rock, the mining experts believe that the established technology used in sulfide ore extraction on land can be directly used for deep-sea SMS deposit mining[6].

Thus, by combining relevant established mining technologies used on the land with the recent development of technologies in marine engineering, SMS deposit mining is technically feasible. However, a lot of development will be required to realize large-scale commercial exploitation

2.2 SMS deposit mining system designed by Nautilus Minerals

The first mission of the mining system is to break huge minerals into a recoverable size, collect the fragments of deep-sea minerals, and then transport the mineral fragments to a support vessel in some way. At the end of 1950 s, comprehensive research and onsite test were conducted by many scientists from many developed countries and consortiums and a lot of deep-sea mining solutions were proposed. The most famous was the system proposed by the marine management company(Ocean Management Inc., OMI) funded by the United States, Japan, Canada, Germany, and other countries. Considering the similarity of the deep-sea environment, a mining system for SMS deposit mining and pipe lifting system were put forward by Nautilus Minerals which is shown in Fig. 4[7–9]. According to the company reports, the appropriate production tools for SMS deposit mining will be transported to the mining area and the corresponding control system, feedback system, collection and detection system will be tested and subsea production plan will be started in 2018[10–12].

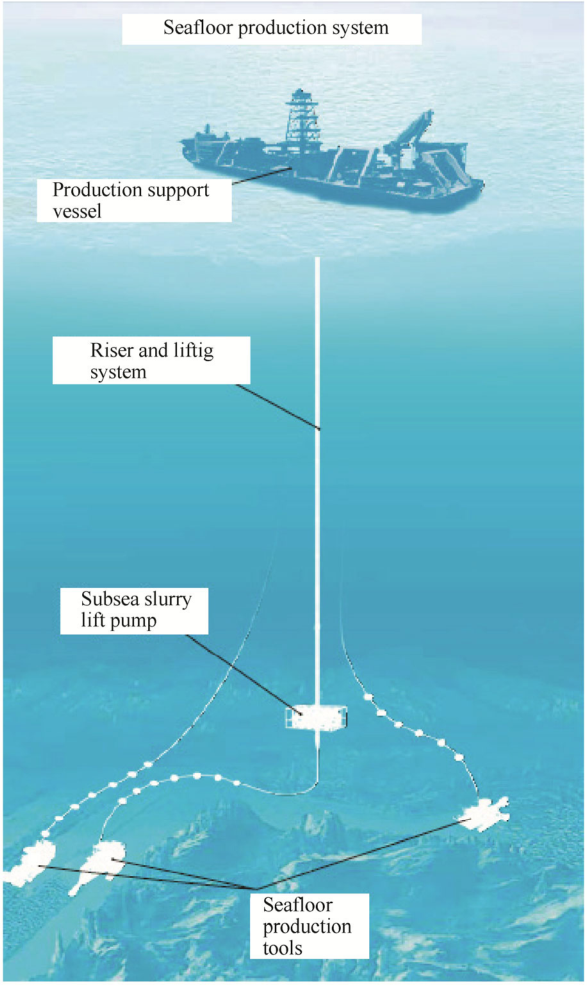

Fig. 4. Mining system of SMS deposits proposed by Nautilus Minerals[10]

2.2.1 Seafloor production tools(SPTs)

There are three types of seafloor production tools (SPTs)[13]: the auxiliary cutter(AC), the bulk cutter(BC), and the collecting machine(CM)[12–13].

2.2.1.1 Auxiliary cutter

The AC is used to disaggregate ores on the seafloor by excavating material through a continuous cutting process, unlike coal or other bulk continuous mining machines on land. The AC is a preparatory tool that deals with rough terrain and creates platforms for the other tools from which to work.

The AUX is a tracked system with studs to provide additional traction. The rock cutting head of the AUX is mounted on an articulated hydraulic arm consisting of slew pivot and boom. The arm provides a very versatile mount for the cutter and allows a large volume of rock to be cut without moving the AUX itself. Although somewhat different in application, the AUX is very similar to diamond mining machines in some aspects. An articulated boom mounted cutter is used on a 250 ton diamond mining machine which is shown in Fig. 5, and the AUX is shown in Fig. 6.

Fig. 5. 250 t Diamond Mining Machine with slewing arm[13]

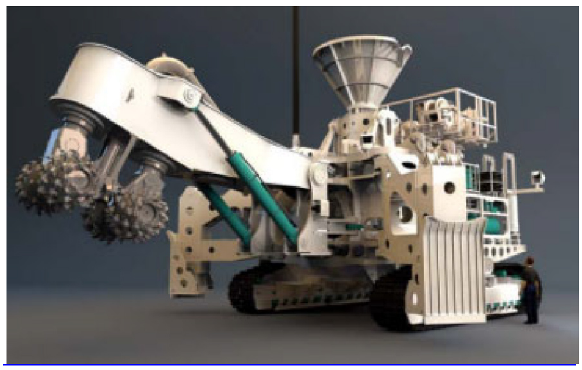

Fig. 6. Auxiliary cutter(AC)[12]

2.2.1.2 Bulk cutter

The bulk miner(BM) is a large track mounted cutting machine that will undertake the bulk of cutting operations.

The purpose of the Bulk Miner is cutting and grinding the bulk of the minerals in the most efficient and practical way as it can.

The BM cuts the mineral but does not gather any material. The BM is shown in Fig. 7, and the onshore road miner tools for cutting coal are shown in Fig. 8. From the picture, the BM is very similar to mining tools used for cutting coal in Fig. 8.

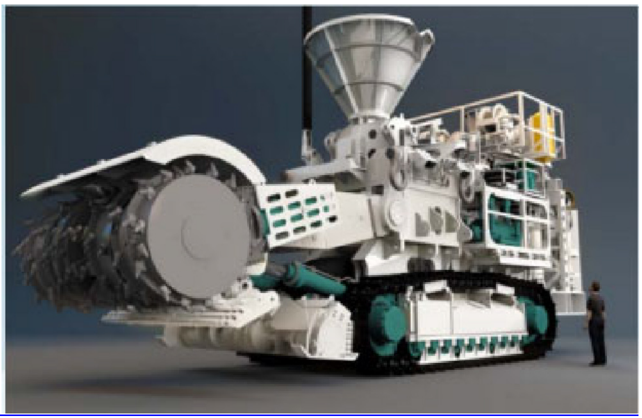

Fig. 7. Bulk cutter(BC)[12]

Fig. 8. Onshore road miner tools for cutting coal[13]

2.2.1.3 Collecting machine

The BC and the AC machines leave mineral fragments on the seafloor for collection by the CM. The CM, also a large robotic vehicle, will collect the mineral fragments by drawing it in with seawater slurry using internal pumps and pushing it through a pipe to the Riser and Lifting System shown in Fig. 9.

2.2.2 Riser and lifting system

The riser and lifting system(RALS) is designed to lift the mineralized slurry to the production support vessel(PSV) using a Subsea Slurry Lift Pump(SSLP) in a vertical riser system. The mixture of seawater and rock is delivered to the SSLP at the base of the riser where it is pumped to the surface via a gravity tensioned riser suspended from the PSV. The RALS comprises a large pump and rigid riser pipe suspended from vessel that delivers the slurry to the surface of the PSV.

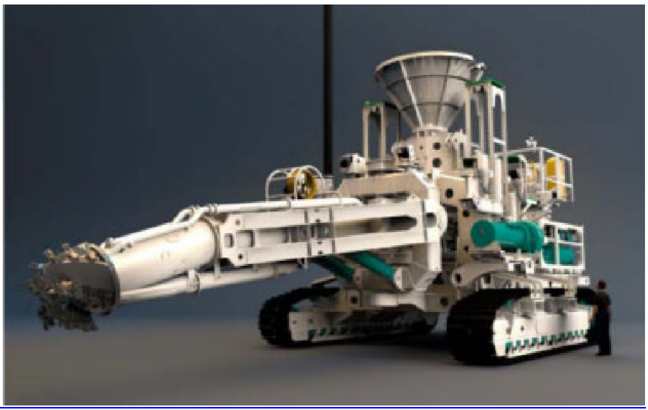

Fig. 9. Collecting machine(CM)[12]

The SSLP is a key piece of equipment in Nautilus Minerals' plan to transport metal minerals from the seafloor. Working with a small environmental footprint, the SSLP enables the transfer of the mineralized material as slurry from the seafloor to PSV with no interaction with the outside water shown in Fig. 10.

Fig. 10. Subsea slurry lift pump(SSLP)[10]

2.2.3 Production support vessel

The production support vessel(PSV) provides a stable platform for operations using global positioning technologies that ensure it stays on location irrespective of weather conditions. The PSV is designed for use in offshore construction and seafloor mining. The PSV is equipped with a moon pool through which the subsea slurry and lift pump(SSLP) and riser system can be deployed. On the deck of the PSV, the slurry is dewatered. The dewatered ores are stored temporarily in the hull of PSV and then discharged to a transportation vessel moored alongside the PSV every 5–7 d. Filtered seawater is pumped back to the seafloor through the riser pipes, which provides hydraulic power to operate the SSLP.

2.2.4 Progress of mining SMS deposits by Nautilus Minerals

Nautilus Minerals, as a pioneer in the exploitation of deep sea SMS deposit, makes a lot of contributions in the field of exploration, and plays a crucial role in the exploitation of SMS deposits[14–15].The concepts of mining were put forward by Nautilus Minerals, which are widely inspired marine scientists from many countries. The company's technical section is described in details in the previous section, and the progress of Nautilus Minerals can be found from the latest company annual report[10]: the SPTs and the RALS including the SSLP are to be finished by the end of 2016; and the final component of the seafloor production system, the PSV is to be completed by the end of 2017; seafloor mineral production will commence and operate in the Bismarck Sea of PNG in the first quarter of 2018.

2.3 SMS deposit mining technical research and sea trial in Japan

In recent years, a series of plans to explore SMS deposits were published and a series of onsite tests were carried out on the SMS deposits on the seafloor by the Japanese team. The development plan was divided into two stages[16]: the first stage(2009–2012) includes a detailed report of the known SMS deposits in the EEZ, the baseline survey of the marine environment, the establishment of the environmental impact prediction model and the development of pilot mining experimental prototype for SMS deposits; the second stage(2013–2018) includes the exploration of new SMS deposits, carrying out environmental impact validation experiments and designing the sample mining machine for SMS deposits.

A similar SMS deposit mining system was proposed in Japan which is shown in Fig. 11[17]. This mining system consists of mining support vessel, mining machine, submerged pump unit, riser pipe, etc. The mining machine is remotely controlled through an umbilical cable. The mining machine is used to collect and dredge ores. A submerged pump is connected to the machine by a flexible pipe to lift the ores up to the support vessel through a riser pipe. The recovered ores are stored in the mining support vessel and transported to the smelters by other ships. Comparing the Japanese proposal with mining tools designed by Nautilus Minerals, only one mining tool was designed to combine the collecting and cutting stages as laid out in Japanese system.

Until 2013, about 20 percent of pilot commercial mining system for SMS deposits was completed and the mining trial was carried out on the seabed SMS deposit at the depth of 1600 m in the Okinawa Trough in November 2012[18].

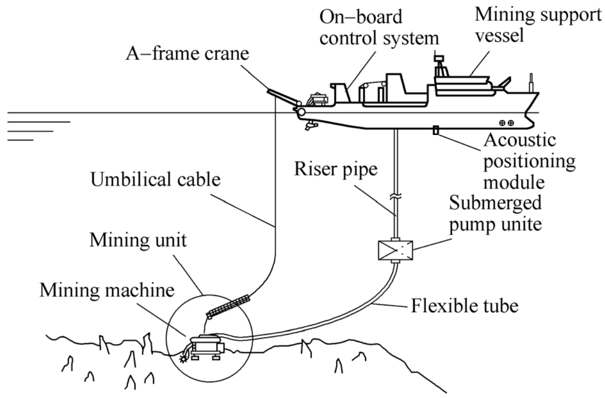

Fig. 11. Mining system proposed by Japan

Manufacturing of the pilot mining machine[17] was completed and delivered to Japan Oil, Gas and Metals National Corporation(JOGMEC) in March 2012. The land and onsite tests were conducted using this system in August 2013 and January 2014 respectively. The structure of the mining machine[17] for SMS deposits proposed by the Japanese team is shown in Fig. 12, and the structure of the mining cutter[17] for SMS deposits designed by the Japanese team is shown in Fig. 13.

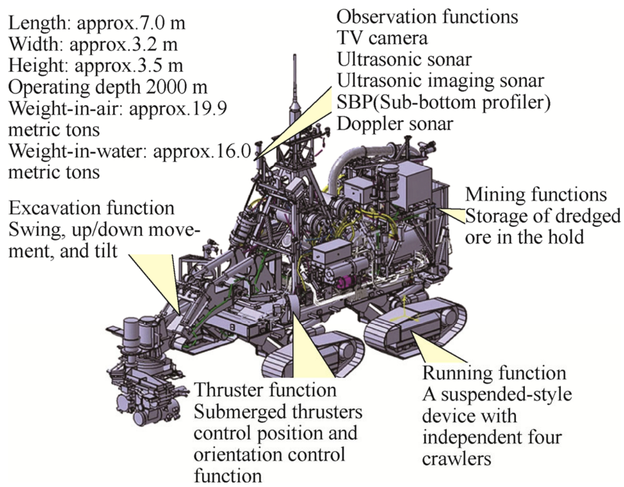

Fig. 12. Structure of SMS deposit mining machine developed by Japan

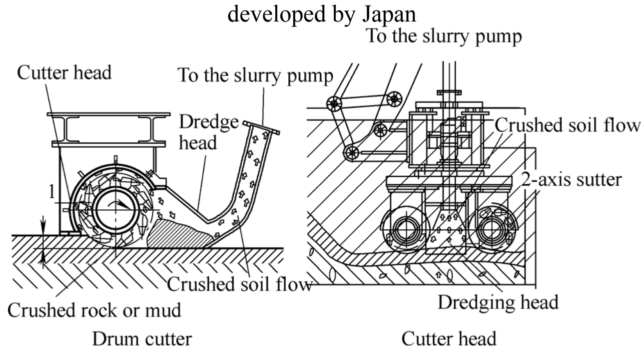

Fig. 13. Structure of the mining cutter of SMS deposit in Japan

3 SMS Deposit Mining Technical Research in China

China owns seabed areas of multi-metallic nodules, cobalt-rich crusts and SMS and has become the first country which has three kinds of mineral seabed areas on the seafloor. For SMS deposits, many resources were invested by Chinese teams in the seabed areas to complete the corresponding survey work.

The mechanical properties of SMS deposits[19], and the simulation and optimization of the roller cutting were studied by the deep-sea research team from the College of Mechanical and Electrical engineering of Central South University[20]. The uniaxial/triaxial test of SMS specimens are shown in Fig. 14.

Fig. 14. Specimens of SMS deposit

For the mining tools, the basic requirements for the cutting and mining of SMS deposit include the following two points: the first is efficiency and the second is environmental protection. The operation of mining must, as far as possible, be done to reduce the pollution created in the process. Based on the above requirements, a dual roller mining tool was proposed by Central South University in which the operation of cutting and collecting SMS deposit are integrated together[21]. The new mining device for deep-sea SMS is shown in Fig. 15.

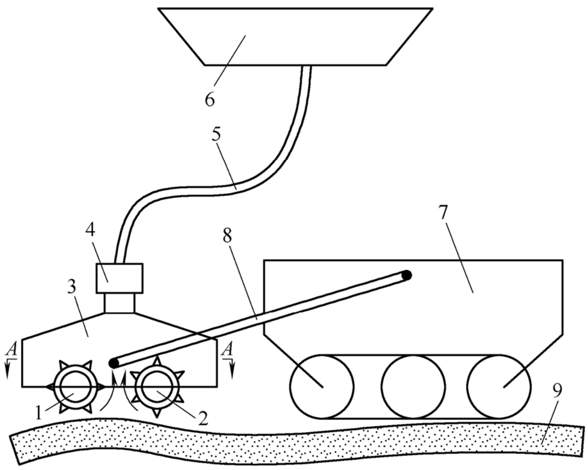

Fig. 15. New mining device for deep-sea SMS deposit

1. Left roller; 2. Right roller; 3. Collecting cover; 4. Lifting pump; 5. Lifting pipe; 6. Mining ship; 7. Ore trolley, 8. Rocker arm; 9. SMS Deposit.

This mining tool comprises left and right rollers, collecting cover, lifting pump, pipeline, mining ship, mining trolley and rocker arm. The left and right cutting rollers are used to cut ores from the SMS deposit. The collecting cover is used to avoid polluting the surrounding environment during the mining process. The ore trolley is designed to drive the whole tool forward and the pipeline is the transportation channel for the extracted minerals. Using this method, pollution of the environment can be reduced effectively in deep sea condition.

4 New Trends in Mining Technology of SMS Deposits

4.1 Multi rollers cutting tools

Since the 1990 s, mining cobalt-rich crust was studied, and a roller mining method was proposed by scientists in the USA, Russia and Japan[8]. A single vibrating roller cutter for deep-sea minerals was designed by scientists from the College of Mechanical and Electrical Engineering of Central South University. Some simulation tests, experiments and optimized designs were carried out using this system[22–25]. In recent years, it has been realized that the single roller cannot meet the requirements of the marine mining industry. The Auxiliary Cutter designed by Nautilus Minerals has multi rollers and the mining tool designed by JOGMEC is also a multi rollers tool. The main consideration is the efficiency as well as other factors, and a corresponding double roller cutter for SMS deposit mining was designed by the scientists from Changsha Research Institute of Mining and Metallurgy. The cutting experiments were carried out under the double roller tool in the lab.

4.2 Environmental protection of mining equipment

According to the requirements of the International Seabed Authority, an increasing number of policies are being published to strengthen the management of deep sea areas. Many scientists recognize that environmental issues are becoming more and more important for the deep sea mining industry[26–27] and a variety of tailing placements and pollution treatment programs were put forward for discussion[28]. For example, an assessment of the ecological impact for tailings return was proposed by WIEBE, et al[29].

4.3 Intelligent mining tools

Due to the special conditions of the deep sea environment, human cannot access the mine sites as easily as land mines. Therefore, more strict requirements are being demanded by the marine mining industry. With the development of artificial intelligence, self-learning and twin robot technology[30–32] is likely to be applied in marine mining industry. For example, an intelligent mining tool with self-learning concept was put forward by CHUNG, et al[33], which could be developed for use in the marine mining of SMS deposits.

5 Conclusions

(1) Due to mineral grade, distribution characteristics and depth of mineral, it is possible for SMS deposits to become the first solid metal mineral to be the subject of commercial exploitation on the seafloor.

(2) The mining application and commercial exploitation of SMS deposits are speeding up in some countries, and some exploitation tools have been proposed and studied by the teams from Nautilus Minerals and Japan. The production tools designed by Nautilus Minerals include the AC, the BC, and the CM, but the exploitation tools designed by the Japanese team integrate cutting and collecting functions into a single machine.

(3) A lot of work on mining SMS deposits has been done by the Chinese team. For example, a double drum cutter for SMS deposits has been tested in the lab; however, compared with developed countries, there is still a lot of development required.

(4) Based on the experiences from mining other minerals, new ideas and methods are being put forward by some scientists that show potential for being developed into new ideas for the commercial exploitation of SMS deposits in the future.

References

[1] BOSCHEN R E, ROWDEN A A, CLARK M R, et al. Mining of deep-sea seafloor massive sulfides: A review of the deposits, their benthic communities, impacts from mining, regulatory framework and management strategies[J]. *Ocean & Coastal Management*, 2013, 84(6): 54–67.

[2] HOAGLAND P, BEAULIEU S, TIVEY M A, et al. Deep-sea mining of seafloor massive sulfides[J]. *Marine Policy*, 2010, 34(3): 728–732.

[3] BAKER E T, GERMAN C R. On the global distribution of mid-ocean ridge hydrothermal vent-fields[J]. *Geophysical Monographs Series*, 2004(148): 245–266.

[4] WU Changbin, LIU Shaojun DAI Yu. Exploitation situation and prospect analysis of seafloor polymetallic sulfides[J]. *Marine Bulletin*, 2008, 27(6): 101–109. (in Chinese)

[5] PETERSEN S. Modern seafloor massive sulfide deposits: challeges and opportunities(C)// *Brazilian-German Year of Science, Workshop on Opportunities in Geosciences and Geotechnology*, Santos, Brazil, 12, Feb, 2011: 8.

[6] MCDONALD Simon. *Annual report 2006*[R]. Sydney: Neptune Minerals Inc, 2007.

[7] MCFARLANE J, BROCKETT T, HUIZINGH J P. *Analysis of mining technologies developed in the 1970's and 1980's*[R]. Kingston: International Seabed Authority, 2008.

[8] RAJESH S, GNANARAJ A A, VELMURUGAN A, et al. Qualification tests on underwater mining system with manganese nodule collection and crushing devices[C]//*Proceedings of the 9th ISOPE Ocean Mining Symposium,* Maui, Hawaii, USA, June 19–24, 2011: 110–115.

[9] HONG S, KIMG H W, CHOI J S, et al. A self-propelled deep-seabed miner and lessons from shallow water tests[C]// *Proceedings of the ASME 29th International Conference on Ocean, Offshore and Arctic Engineering*, Shanghai, China, June 6–11, 2010: 75–86.

[10] HEYDON D. *Annual report 2015*[R]. Sydney: Nautilus Minerals Inc, 2016

[11] TAN Thomas. *Nautilus's seafloor production tools arrive in Oman*[R]. Sydney: Nautilus Minerals Inc, 2016.

[12] HEYDON D. *Annual report 2012*[R]. Sydney: Nautilus Minerals Inc, 2013

[13] SRK Counsulting. *Offshore production system definition and cost study*[M]. Sydney: Nautilus Minerals Inc, 2010

[14] RIDLEY N, GRAHAM S, KAPUSNIAK S. Seafloor production tools for the resources of the future[J]. *American Journal of Operations Research*, 2011, 2(12): 1379–1382.

[15] STEVENSON I, LOWE J, PLUNKETT S. New technologies for deep-ocean seafloor resource exploration[J]. *Sea Technology*, 2010, 51(9): 34–37, 39.

[16] NARITA Teruyoshi, OSHIKA Junya, OKAMOTO Nobuyuki, et al. Summary of environmental impact assessment for mining seafloor massive sulfides in Japan[J]. *Journal of Shipping and Ocean Engineering*, 2015(5): 103–114.

[17] ISHIGURO Shinji, YAMAUCHI Yoshiaki, ODAKA Hiroyuki, et al. Development of mining element engineering test machine for operating in seafloor hydrothermal deposits[J]. *Mitsubishi Heavy Industries Technical Review*, 2013, 50(2): 21–26.

[18] KAWANO S, KAWAI T, MASUDA N, et al. Study on mining system for seafloor massive sulfide mound and results of on-site excavation tests in Okinawa Trough[J]. *Shigen-to-Sozai*, 2015, 131(12): 614–618.

[19] HU Wang. *The numerical simulation of solid-liquid two-phase flow of the suction process of SMS particles*[D]. Changsha: Central South University, 2014. (in Chinese)

[20] XU Yingguang, LIU Shaojun, HUANG Zhonghua. Simulation analysis of cuting SMS and optimization of load fluctuations[J]. *Simulation of Compute*r, 2014, 31(11): 240–244. (in Chinese)

[21] Central South University. *A new device for cutting SMS*[P]. China: 2011103872253, 2011–11–29. (in Chinese)

[22] HALKYARD J. Technology for mining cobalt-rich manganese crusts from seamounts[J]. *Ocean(New York)*,1985: 352–372.

[23] CHEN Yuanyi. *Parameter optimization and dynamic simulation of collection head of spiral drum of cobalt-rich crust*[D]. Changsha: Central South University, 2011. (in Chinese)

[24] ZHANG Zhenhua. *Research Cobalt crust spiral mining head cutting pick fragmentation characteristic and arrangement optimization*[D]. Changsha: Central South University, 2012. (in Chinese)

[25] XIA Yiming, ZHANG Gangqiang, NIE Sijun. Optimal control of cobalt crust seabed mining parameters based on simulated annealing genetic algorithm[J]. *Journal of Central South University of Technology*, 2011, 18: 650–657.

[26] ANDREA Koschinsky, GERD Schriever, PEDRO Martinez Arbizu. Revisiting the DISCOL area in the Peru Basin 25 years after the disturbance experiment—a German/European initiative to prepare an environmentally sustainable manganese nodule mining[C]//*The 42nd Conference of The Underwater Mining Institute*, Copacabana, Rio De Janeira, Brazil, Oct 21–25, 2013: 141–148.

[27] DV Ellis. A review of some environmental issues affect marine mining[J]. *Marine Georesources and Geotechnology*, 2001, 19(1): 51–63.

[28] RAMIRE-LLODRA E, TRANNUM H C, EVENSET A, et al. Submarine and deep-sea mine tailing placements: A review of current practices, environmental issues, natural analogs and knowledge gaps in Norway and internationally[J]. *Marine Pollution Bulletin*, 2015, 97(1–2): 13–35.

[29] WIEBE Boomsma, ALEYDA Ortega, LYNYRD de Wit. Towards zero impact: Assessment of ecological impact for tailings return[C] //*The 42nd Conference of the Underwater Mining Institute*, Copacabana, Rio De Janeira, Brazil, Oct 21–25, 2013: 41–50.

[30] PAN Yang, GAO Feng, QI Chenkun, et al. Human-tracking strategies for a six-legged rescue robot based on distance and view[J]. *Chinese Journal of Mechnical Engineering*, 2016, 29(2):

219–230.
[31] LEI Jingtao, YU Huangying, WANG Tianmiao. *Dynamic bending of bionic flexible body driven by pneumatic artificial muscles(PAMs) for spinning gait of quadruped robot*[J]. *Chinese Journal of Mechnical Engineering*, 2016, 29(1): 11–20.
[32] LU Zongxing, XU Chunguang, PAN Qinxue, et al. Automatic method for synchronizing workpiece frames in twin-robot nondestructive testing system[J]. *Chinese Journal of Mechnical Engineering*, 2015, 28(4): 860–868
[33] CHUNG J S. Track-keeping contril of Seafloor miner by successive learning of unknown velocity and soil properties[C]//*Proceedings of the 3rd Ocean Mining Symposium*, Goa, India: ISOPE, 1999: 85–92.

Biographical notes

LIU Shaojun, born in 1955, is currently a professor at *College of Mechanical and Electrical Engineering, Central South University, China*. He received his PhD degree from *Central South University, China*, in 1997. He has carried on the research of deep-sea mining more than ten years.
E-mail: liushaojun@mail.csu.edu.cn

HU Jianhua, born in 1977, is currently a PhD candidate at *Central South University, China*. He received his master degree on mechanical degree in *Central South University, China*, in 2003. His research interests include ocean engineering and mechanical simulation.
E-mail: hujianhua2008@hotmail.com

ZHANG Ruiqiang, born in 1992, is currently a postgraduate candidate at *Central South University, China*. His research interests include gear transmission and ocean engineering.
E-mail: 1130816396@qq.com

DAI Yu, born in 1981, is currently an associate professor at *College of Mechanical and Electrical Engineering, Central South University, China*. He received his PhD degree from *Central South University, China*, in 2010. His research interests include mechanical lubrication system and ocean engineering.
E-mail: daiyu_6@aliyun.com

YANG Hengling, born in 1982, is currently a PhD candidate at *Central South University, China*. His research interests include intelligent control engineering and mining engineering in deep sea.
E-mail: 65065325@qq.com