Machines for Mechanical Mining of Hardly Workable and Abrasive Rocks

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INTRODUCTION

Mechanical mining is used wherever various types of rocks, concrete or road surfaces are used. A lot of exploited raw materials, such as hard coal and lignite, stone and potassium salts or snow soda, are easily worked. However, there is an increasing need for effective extraction of hardly workable and abrasive rocks, such as granite, basalt, sandstone, melaphyre, porphyry or dolomite. TBM machines work very well when drilling long tunnels, but they are not suitable for the exploitation of useful minerals by standard mining methods. Similarly to drilling a shaft, which is a separate problem (Krauze, 2018). Mechanical properties of rocks determine the method of their mining. The most common mechanical properties are defined by uniaxial compression strength. However, the efficiency of the mining process is also affected by abrasiveness, which influences the rate of tool abrasive wear. Drilling and blasting are widely used to mine hardly workable rocks. This is a well-known and tested method, which does not entail big initial expenditure. However, it requires the use of explosives (threat, rock mass cracking, withdrawal of people, smoke) and generates high operating costs. In addition, sometimes the use of explosives is not allowed, in which case mechanical mining is necessary. Currently, in the case of hardly workable abrasive rocks, the most common method is mining with discs by rear undercutting. Undercutting can be applied simultaneously with high pressure water jets or with disk oscillation. Typically, the cutterheads of various types of working machines are equipped with conical picks. These tools are also used in the case of hardly workable rocks, for example to equip cutting heads of roadheaders.

Methods of mechanical mining of hard, extremely difficult-to-cut and abrasive rocks have been sought for many years (Biały, 2014, Biały, 2016, Bołoz and Krauze, 2018, Fries et al., 2016, Krauze et al., 2015, Stopka et al., 2013, Dehkhoda and Detournay, 2019). The development of a system for mining this type of rock requires solving a number of problems related to tool life (Gajewski et al., 2008, Krauze et al., 2015, Kotwica, 2018).

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In the article, selected methods of mechanical rock mining as well as selected machines and machine systems have been described. The authors have focused on rock mining machinery, so only some of the solutions applied in tunnelling have been presented. It should be noted that typical tunnelling machines are TBMs (Tunnel Boring Machines). Typical tunnel solutions, such as Aker Wirth MTM 4, MTM 6 or TBE500, have also been omitted. Information on tunnel machines can be found in the literature (Vogt, 2016, Sifferlinger at all, 2017, Kotwica and Małkowski, 2019, Ramezanzadeh and Hood, 2010).

METHODS OF MECHANICAL MINING OF ROCKS

Mechanical mining of rocks involves many methods, such as drilling, cutting and planing. Basically, these methods utilize the processes of cutting, undercutting (chipping), impact mining or mining by static pressure. In addition to these methods, in opencast mining or civil engineering, digging and ripping are used to mine grounds and weak rocks. In the case of building raw materials mines, the material is obtained in the form of blocks, for example, by means of diamond wire saws, and in the later stages of processing, also with circular saws. Over the years, unconventional methods, such as thermal breaking and electro-hydraulic mining, waterjets, laser and others have also been tested (Vogt, 2016).
According to International Society for Rock Mechanics, rocks within a range of 50 MPa to 100 MPa are characterized by high strength, within a range of 100 MPa to 250 MPa – by very high strength, whereas those over 250 MPa are characterized by extremely high strength (Vogt, 2016). At the same time, rock abrasiveness can be described by e.g. Cerchar Abrasiveness Index (CAI), which varies from not abrasive (below 0.5) to extremely abrasive (above 4.5). Abrasiveness can also be determined by means of specific tool wear or laboratory sampler wear (Mucha, 2019).
In the case of abrasive rocks with strength above 120 MPa, cutting heads with conical picks are characterized by significantly reduced efficiency. For this reason, either special cutterhead solutions are used, or disc cutting by static pressure or rear undercutting are applied. Drilling with boring heads also utilizes static pressure for cutting and is used for drilling holes and tunnels. When drilling tunnels, TBMs cut rocks characterised by the highest strength indexes thanks to the huge clamping force of the head (about 8 MN). However, for the exploitation of minerals now the future is seen in disc mining by static pressure, rear undercutting. In recent years, the method of undercutting with simultaneous disk oscillation has been intensively developed.
Comparative tests of mining sandstones with a strength of 36 MPa revealed very large differences in the cutting forces on the disk. In the case of discs, the most important parameter is the clamping force, which for a classic disk cutting by static pressure was 18 kN, while for undercutting – 6.8 MPa. Application of oscillation allowed for reducing this force to 1.8 kN, which is a ten times lower value than traditional static pressure (Dehkhoda and Detournay, 2019).

Over the past years, many unique solutions of mining machines have been proposed. Some solutions have been developed as part of special mining systems, i.e. sets of machines, while others are separate machines. These machines utilize the presented mining methods (Ramezanzadeh and Hood, 2010, Sifferlinger at all, 2017, Vogt, 2016, Kotwica and Małkowski, 2019, Dehkhoda and Detournay, 2019).
Disc tools, conical picks and boring heads are equipped with tips made of tungsten carbide (WC). Cemented carbides work very well in most cases, but their durability decreases with rock strength and abrasiveness. A material much more resistant to abrasive wear, which has been tested by many leading machine manufacturers, is synthetic diamond (polycrystalline diamond or PCD). The German manufacturer Element Six GmbH (E6) is a leading producer of tools made of a combination of cemented carbide and synthetic diamond.

MACHINES FOR MINING HARDLY WORKABBLE ROCKS

Roadheaders are well tested constructions which enable excavating workings and tunnels of various sizes. When analysing such shearers from the point of view of cutting hardly workable rocks, it is worth listing the largest models in the world. Based on ICUTROC technology, Sandvik has developed heavy roadheaders for cutting rocks the strength of which does not exceed 120 MPa (Fig. 1).

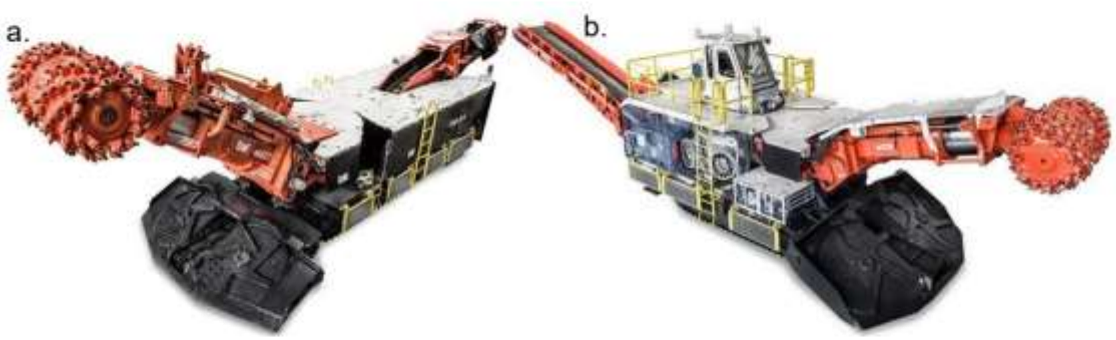

Fig. 1 ICUTROC roadheader produced by Sandvik:
a. MH621 hard-rock miner, b. MT720 crawler-mounted boom-type roadheader

Sandvik's design goal was to develop a machine for cutting such rocks in an economically justifiable manner. The latest model is Sandvik MH621 hard-rock miner (Fig. 1a) for mining excavations with a width of 4.5 m to 8.5 m and a height of 3.8 m to 5.8 m with a total weight of 125 Mg. The second, intended for tunnelling and rock exploitation, is the MT720 roadheader (Fig. 1b), which cuts the width from 5.5 m to 9.1 m, at a height from about 5 m to 6.6 m, with a mass of approximately 130 Mg. The MH621 model is designed for work in underground mines, whereas MT720 is intended, among others, for excavating subway tunnels, road tunnels or for the maintenance of existing mining excavations. Both of these Sandvik roadheaders are equipped with a 300 kW boom and a cutterhead drive with an output of 300 kW.

It is also worth mentioning the largest machines produced by the Chinese company SANYHE International Holdings Co. Ltd. (Sanyi) and the German company Aker Wirth GmbH (Wirth). The EBH418 shearer (Fig. 2a), produced by Sanyi, with a total weight of up to 160 Mg is currently the heaviest roadheader. It is designed for excavations with a width of 4.0 m to 8.4 m and a height of 4.0 m to 6.1 m. However, the limit value of rock strength is 130 MPa, despite the cutterhead drive power of 418 kW. On the other hand, the T3.20 roadheader (Fig. 2b), produced by Wirth, is intended for excavating tunnels in rocks with uniaxial compressive strength of up to 150 MPa. The T3.20 roadheader is equipped with a 300 kW longitudinal cutterhead drive and a boom. With a mass of 135 Mg, it can make an excavation having a cross-section surface of 20 m^2 to 72 m^2. The maximum width of the excavation is ca 9.5 m and the height – approximately 7.9 m.

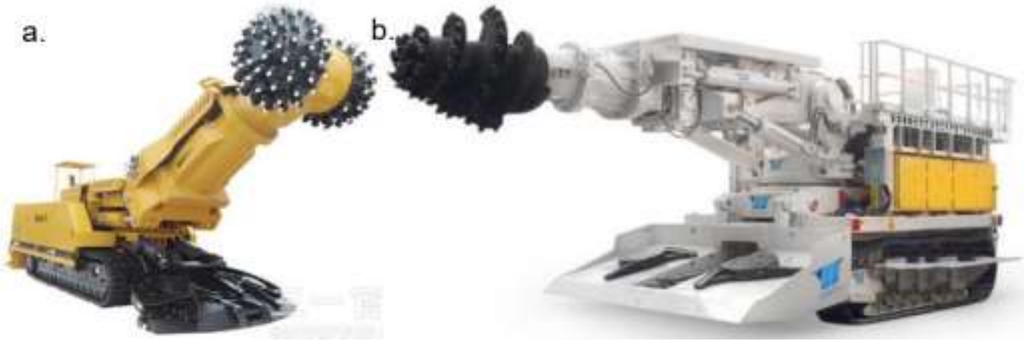

Fig. 2 Heavy roadheaders:
a. Sanyi EBH418, b. Wirth T3.20

Among the machines for mining hardly workable and abrasive rocks, in addition to typical roadheaders, there are several unique designs. Since 2018, Atlas Copco has been operating as two separate companies, Atlas Copco and Epiroc. Epiroc focuses on the market of mining, construction and natural resources industries. The name was chosen from among more than 1000 proposals and is a combination of the Greek "on" (epi) and the abbreviated "rock" from English (roc). Epiroc offers a series of three roadheaders: Mobile Miner 22H (Fig. 3), Mobile Miner 40V (Fig. 4) and Mobile Miner 55V.

Fig. 3 Epiroc Mobile Miner 22H – in a platinum mine in South Africa

Fig. 4 Epiroc Mobile Miner 40V

The markings are derived from the dimensions of the machine and the horizontal (H) or vertical (V) orientation of the disc cutterhead. It is worth mentioning that each of these machines makes an excavation of a slightly different shape. In Fig. 5, the total weight and power of each model have been given in addition to the shape and dimensions of the excavation as well as the diameter and orientation of the cutting head.

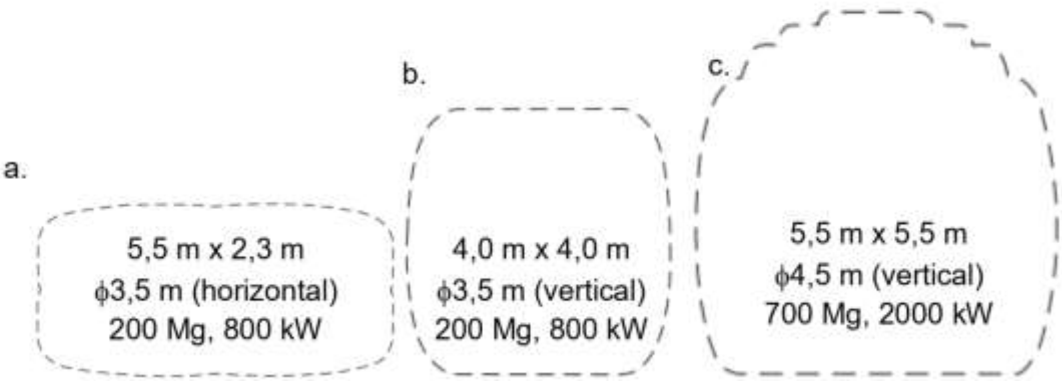

Fig. 5 Shape of profile made by Mobile Miner: a. 22H, b. 40V, c. 55V

The machines are equipped with systems supporting the operator's work. The Mobile Miner series is designed for cutting rocks with a strength of up to 150 MPa. These machines are comparable in mass and length to typical TBMs. Most of the machines presented in the article are characterized by 1 kV or 1.14 kV supply voltage, while the Mobile Miner series is adapted to 1 kV, 4.16 kV and 13.8 kV, respectively.

Joy Global Inc., being part of Komatsu Mining Corp., together with CRCMining are working on a technology known under the trade name DynaCut. DynaCut uses the method of undercutting with discs, which, however, oscillate simultaneously and, thus, significantly increase the efficiency of cutting – the ODC (Oscillating Disc Cutter) method.

The first prototype Surface Rig 1 SR1 machine (Fig. 6a) was equipped with one oscillating disc and the mining process was supported by a high pressure water jet. The second version called HRCM10 (Hard Rock Continuous Miner) is designed to work in an excavation of 1.0 m height. The HRCM10 roadheader was tested in a platinum mine in South Africa (Fig. 6b). Information about these machines, in contrast to ODC/DynaCut technology, is scarce (Joy, 2020), (Vogt, 2016).

Fig. 6 DynaCut Joy i CRCMining machines:
a. SR1, b. HRCM10 in a platinum mine

In recent years, Sandvik has presented the MX650 Rapid Mine Development System – a machine which also utilizes the undercutting method. This roadheader is equipped with two disc cutterheads attached to swing arms in two planes (Fig. 7).

Fig. 7 Sandvik MX650 Rapid Mine Development System
Source: (Bergbaunewsletter 2017)

In 2017, MX650 was tested at a tungsten mine in Austria (Wolfram Bergbau and Hütten AG in Mittersill), as part of the Rock Vader project funded by EIT Raw Materials. The roadheader was designed to cut rocks characterised by strength of up to 250 MPa, with a potential of excavating a 5m x 5m gallery. In the case of such cross-section and abrasive rocks with a strength of 150 MPa, MX650 achieves an advance of 20 m per day. Next, the machine was supposed to work at the Petra Diamond's Finsch diamond mine in South Africa. The project was scheduled to end on 31/12/2019, but no official information has yet been made available (Bergbaunewsletter 2017, Hartlieb, 2017, Hardrock, 2020).

SYSTEMS FOR MINING HARDLY WORKABLE ROCKS

Due to their mode of operation, machines designed for cutting hardly workable rocks are very often part of mining systems. In addition to mining, such systems provide roof protection, mined rock haulage and machine advance in the excavation. Currently, Sandvik's offer (Fig. 8) also includes the MN 220 Continuous reef miner (formerly Alpine Reef Miner ARM1100 produced by Voest Alpine) mining system. This complex is intended for mining in low excavations in the form of veins and deposits. It has a cutting head equipped with disc tools. The combination of the rotational movement of the cutterhead and the swinging motion of the arm allows for cutting the rock mass by the undercut method. The solution is designed for excavations with a height of 1.0 m to 1.1 m. The machine expands in the excavation and cuts the face with a width of ca 4.3 m. It is equipped with a loader, conveyor belt and anchoring tower, owing to which its total length is almost 16 m with a total weight of 32 Mg. The appropriate set of machines allows the process of cutting, loading, haulage and roof protection to take place in parallel. The complex is controlled remotely by means of a radio remote control.

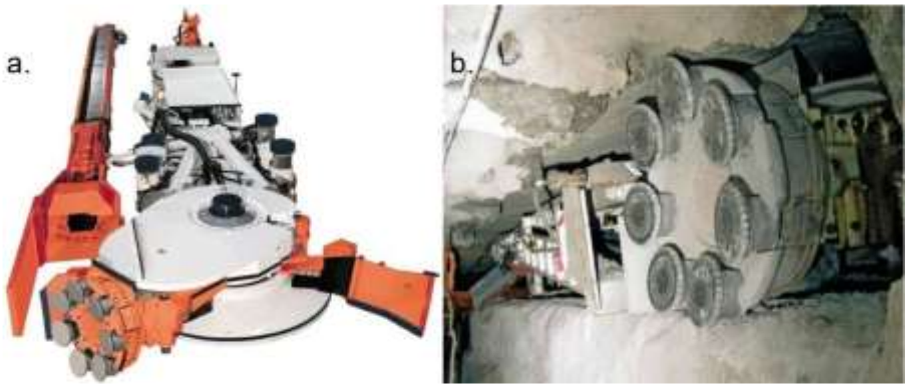

Fig. 8 MN220 system produced by Sandvik:
a. general view, b. installed in an excavation

CAT offers Rock Straight System consisting of the HRS1220 chock support, the HRC30 hard rock conveyor and the HRM220 hard rock roadheader (Fig. 9).

Fig. 9 CAT Rock Straight System:
a. view of cutting heads, b. example of a control panel in the operator's cab

This complex is intended for the exploitation of gold, platinum and copper ores in low excavations. The CAT solution uses a roadheader based on the process of rear undercutting by means of classic conical picks (Fig. 9a). The picks are attached to discs rotating around their axis. The discs are mounted on two cutterheads, which also rotate. In total, the roadheader is equipped with four cutterheads (two for each head) and each of them has seven discs with 18-24 conical picks, which gives a total of 28 discs and 504-672 picks. Both heads are independently driven and attached to independent arms, which allow the cutting height to be changed. The system is designed to work in a face of up to 100m in length and 1.3 m to 2.0 m in height. Each head has a 132 kW drive (a total of 264 kW) and can cut rocks characterized by a strength above 120 MPa. The shearer in the given version weighs about 41 Mg and the support unit – ca 9.3 Mg (1.3 m pitch). The complex is controlled automatically and supervised by one employee (Fig. 9b). The ergonomic cabin is air-conditioned, insulated and meets the ROPS (FOPS) requirements.

DISC HEAD WITH A COMPLEX AGH TRAJECTORY

A unique cutting head (Fig. 10) has been developed at AGH University of Science and Technology to be installed on a heavy roadheader. This head, like some of the previously presented solutions, utilizes the undercutting method (Gospodarczyk et al., 2013, Gospodarczyk et al., 2016).

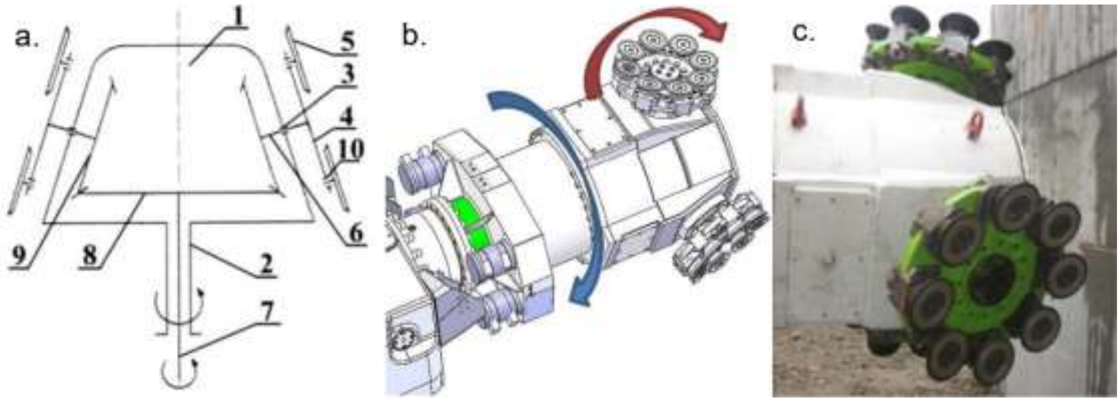

Fig. 10 Disc head: a. kinematic diagram (Gospodarczyk et al., 2013), b. 3D model (Gospodarczyk et al., 2013), c. field test photograph

Source: (Kotwica and Małkowski, 2019)

The disc head concept shown in Fig. 10 is designed for rock mining by the undercutting method as the effect of the complex trajectory of disc tools. The basic design assumption is the independence of the rotational movement of head 1 and the rotational movement of discs 2. In the head body, in sockets 3 there are drive shafts 6 with discs 4, on which 10 disc tools are mounted in bearing seats 5. The drive on shafts 6 is transmitted by internal shaft 7, which is independent from external shaft 2, and by a set of bevel gears 8 and 9. Due to the complex design, the head weighs almost 6 Mg.

AGH SYSTEM FOR MINING COPPER ORES

Another solution developed at AGH University of Science and Technology is a unique system for mechanical mining of copper, iron, zinc and lead ores in the form of more or less regular deposits (Bołoz et al., 2018). The system is designed to enable automatic exploitation of ore deposits within the height range of 1.0-2.0 m, with an average efficiency of 50 Mg/h, in rocks characterized by uniaxial compression strength within a range of 15-200 MPa. Fig. 11 shows a preliminary design of a longwall shearer system consisting of a longwall shearer with one cutterhead 1, a longwall belt conveyor 2, powered roof support unit 3 and a beam stage loader 4. The ends of the face conveyor are equipped with its drives *5* and drives of the shearer advance cable system *6*.

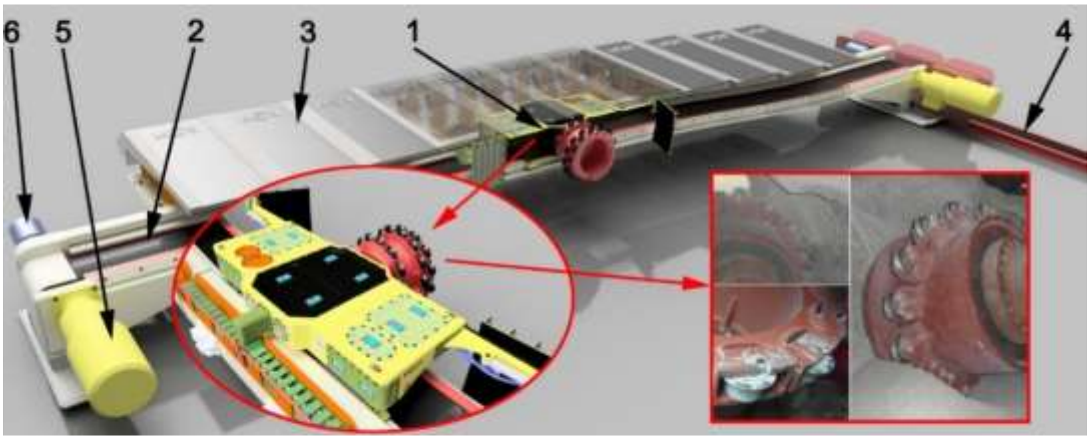

Fig. 11 System equipped with a single-cutterhead shearer
1. shearer with one cutterhead, 2. belt conveyor, 3. chock support, 4. beam stage loader, 5. conveyor's drive, 6. shearer advance cable system

The shearer moves on four skids along the face conveyor's route. The shearer's hull, depending on the system height, can be equipped with cutterhead drive units having various power of min. 2x120 kW. The mining machine works in a longwall system and makes further cuts to the assumed depth (web) in the excavation of a certain height. The shearer works to the full web along the entire length of the face. Separation of the mining process from the loading process allows for achieving the targeted daily production. The use of a belt conveyor significantly reduces the wear of the haulage equipment. The shearer is equipped with a disc cutterhead, which cuts by exerting a static pressure. The face conveyor, powered support and longwall shearer are subject of AGH patents (Bołoz et al., 2018).

CONCLUSIONS

The high demand for some mineral resources as well as the constant pursuing to increase operational efficiency and reduce costs contribute to the development of new mining methods and machines. Exploitation based on blasting is not always possible. In such a case, the only solution remains mechanical mining. In recent years, one can observe faster development of disc cutting machines, in particular ones based on undercutting, which is already a well-known and proven method. Therefore, the vast majority of machines work in this system of mining. Additionally, utilisation of disc oscillation results in a significant reduction of energy consumption in the process. Classic constructions, such as roadheaders having cutterheads equipped with conical picks, are still being developed. In one of the solutions, these picks are also used for mining by the undercutting method. The two presented solutions developed at AGH University of Science and Technology utilize discs. One concerns the roadheader cutting head and utilizes rear undercutting, whereas the other solution designed for the mining of ores is equipped with a disc cutterhead which cuts using the static pressure.

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Abstract: Mechanical mining is a widely used method for separating material from mined rock in the mining branch, tunnelling, road and construction industries. Depending on the mechanical properties of rocks, most often defined by uniaxial compressive strength, various machines and tools are applied. Apart from rock strength, the efficiency of the mining process is determined by abrasiveness, which affects the rate of tool abrasive wear. Currently, disc mining by static pressure or rear undercutting are the most developed methods. Undercutting can be supported by high pressure water jet or disk oscillation. Mining with drills also utilizes static pressure. In addition to discs, conical picks are applied; they are mounted on cutterheads. In underground mining and tunnelling, there is an increasing need to cut abrasive rocks with a strength of more than 120 MPa in places where explosive materials cannot be used. In the article, the recently applied and developed methods of cutting abrasive rocks characterized by high strength, such as copper, gold, tungsten or platinum ores and diamond deposits, have been presented. Next, the latest machines and machine systems used for their mining are reviewed. Leaders in the mining machinery industry, such as Joy (Komatsu), Epiroc (Atlas Copco), Sandvik and Aker Wirth are developing proprietary designs of cutting machines based on both well-known and completely new ideas.

Keywords: hardly workable rocks, mechanical mining of rocks, cutting with disc-shaped tools (disc mining), rear undercutting, mining machines