Need of alternative excavation tools for mining robots

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ABSTRACT

In underground mining, the harsh environment and the possible dangers from rock fall or bursts always leave a certain residue risk to personnel. With the help of fully automated machines and/or autonomous robots it is aimed to access new deposits or re-open abandoned mines can be. Possible tasks for robots in mining are the maintenance of machinery, exploration and excavation.

This work deals with the applicability of excavation tools for small, mobile mining robots. Conventional, mechanical excavation methods play a major role in current underground mining, but their efficiency is severely limited by the rock strength and decreases with smaller scales. The reaction forces generated there are usually high and require a high mass and high power of the mining machine. Within the conducted work, the most promising excavation methods are compared on the basis of defined parameters and their application in different scenarios—taking into account the maximum reaction forces that can be handled by the machine/robot—are evaluated. Based on these studies, the applicability of certain excavation tools for different scenarios and rock strengths are analysed. It could be seen that "conventional", mechanical excavation methods are limited with regard to the maximum compressive strength. Other systems are able to reduce certain disadvantages and limitations by excavating the material by means of alternative energy input. Based on the conclusions and considering defined requirements, a concept of a combined excavation system is presented. The major advantages of this technology are the low reaction forces, the low-wear application, and the environmental friendliness. Firstly, concepts of mechanical drilling tools were developed and simulations of the excavation process were carried out using DEM-simulations to perform preliminary investigations. The results provide a profound basis to conceptualize first ideas of an alternative excavation system for small mining robot and to generate a general prospect.

INTRODUCTION

Future challenges in mining with regard to sustainability and ecological aspects require additional efforts in the area of research and development. With the help of fully automated machines and/or autonomous robots, it should be possible to open up new deposits or reopen and economically operate abandoned mines. Following, potential areas of application have been stated: Machine maintenance, exploration (e.g., of abandoned mines or flooded mines), and tunnelling and mining (especially in hard-to-reach areas). Future scenarios require new approaches and adaptation of existing technologies. Outdated views may need to be phased out to make room for new thinking and to develop innovative solutions that will help make mining of the future more sustainable and economical. The design and technologies used in mining robots may be fundamentally different from conventional machines, as they need to be adapted to meet the new challenges of greater flexibility and mobility. In particular, current mining technologies need to be evaluated against new standards to meet upcoming criteria. (Hiltz, 2020; Siciliano, 2016)

Numerous research and development projects are focused on developing robots for tasks in underground environments. This class of robots is at the other end of the scale when compared to tunnelling and mining machines. The comparatively small mass and low available power are the most limiting factors and therefore require new approaches - in addition to adaptations of commercial off-the-shelf (COTS) products. The interaction between a mining tool and the rock generates forces that the machine must take up. The extent of these reaction forces varies depending on the mining method and rock strength.

Mining methods can be divided into drill and blast, mechanical, alternative and combined mining methods, with the first two being the most commonly used in modern mining. To ensure efficient and economical use, the mining tool must meet a number of requirements, such as adequate advance and excavation performance, which are significantly influenced by the rock to be mined. Furthermore, the grain size distribution of the mined material, wear resistance, general maintenance requirements of the tools and the mobility of the tool (but also of the machine/robot), which are decisive for the branch radius of the machine/robot, have to be considered. (Berner & Sifferlinger, 2021; Sifferlinger, 2021)

METHODOLOGY

In this work, conventional mining methods and their tools were selected and tested for their ability to scale down. This was done by determining the cutting forces for different rock strengths and comparing them with the traction forces of a small mining robot.

Limitations of conventional excavation technologies

The performance of conventional, mechanical mining methods, such as part-or full-face cutting methods, is limited on the one hand by the strength and abrasiveness of the rock to be mined, and on the other hand also by the size and power of the machine. Drill and blast classically represents an economical tunnelling and mining method, but it also brings some disadvantages with it that cannot be neglected. Some of them are safety during the stockpiling, transportation and blasting process, generation of toxic fumes and gases as well as vibrations and noise, overblasting, complexity of automation, discontinuous mining and difficulties regarding automated/autonomous blasting due to the respective legal situation - just to mention a few. Because of these issues, there is a major trend towards the development of fully automated, continuous mining methods. Mechanical mining methods (part- and full-face cutting methods) have manifested as key technologies. These technologies can be used as both tunnelling and excavation methods but are enormously limited (in particular roadheaders) by rock strength and abrasiveness. Solid cutting machines with cutting discs can handle much higher rock strengths but have much less flexibility and mobility than roadheaders. To a certain extent, roadheaders are capable of producing tight curves and junctions, whereas full-face machines have very high junction radii. ***Figure 1*** illustrates the flexibility versus workable rock strength of mechanical tunnelling and excavation machines and identifies a "gap" for new, alternative technologies. (Sifferlinger, Hartlieb & Moser, 2017; Berner & Sifferlinger, 2020)

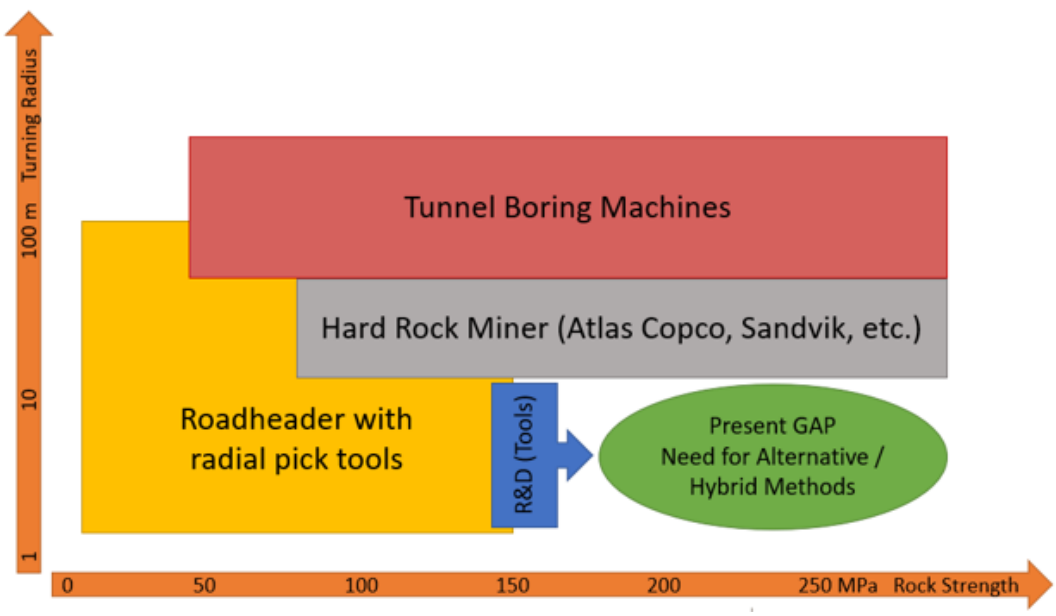

Figure 1: Mobility against excavation power of mechanical excavation machines (*Sifferlinger, Hartlieb & Moser, 2017*)

The higher the strength of a rock, the higher the cutting forces required for it. This information is crucial for the rough design of the cutting tool. As shown in **Figure 1**, strengths up to 130 MPa are economical for part-face cutting technologies. Cutting heads equipped with conical picks are used for this purpose. According to (Evans, 1984; Goktan, 1990; Goktan & Gunes, 2005; Roxborough & Liu, 1995), the required cutting force can be determined as a function of the compressive and tensile strength of the rock. ***Figure 2*** shows the cutting forces for a pick depending on the compressive strength (Uniaxial Compressive Strength - UCS).

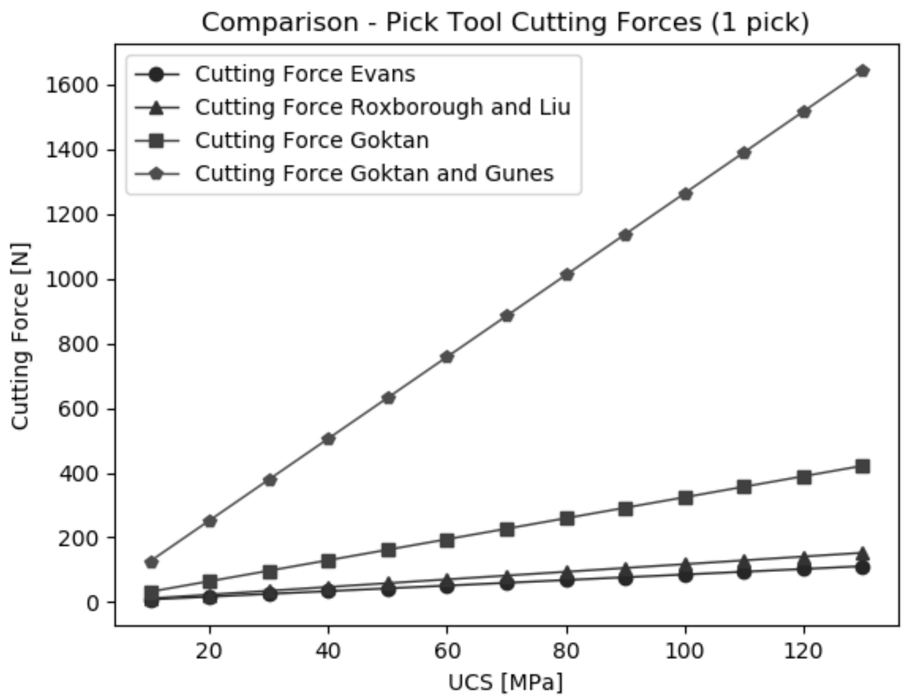

Figure 2: Required cutting force of conical pick tool *to (Evans, 1984; Goktan, 1990; Goktan & Gunes, 2005; Roxborough & Liu, 1995)*

The reaction forces that occur during the cutting process must be taken up by the machine/robot. If one takes into account that several picks are engaged during the cutting process, extremely high reaction forces are generated overall.

Tunnel boring machines and so-called hard rock miners use discs as cutting tools. With the help of these cutting discs, higher rock strengths (up to 300 MPa) can usually be tackled. (Rostami, 1993) developed an approach to estimate the required cutting force of discs by finding a relation between the stress distribution in the contact zone and the resulting force on the disc. ***Figure 3*** shows the curves of the total force and its components as a function of compressive strength (UCS) for a cutting disc.

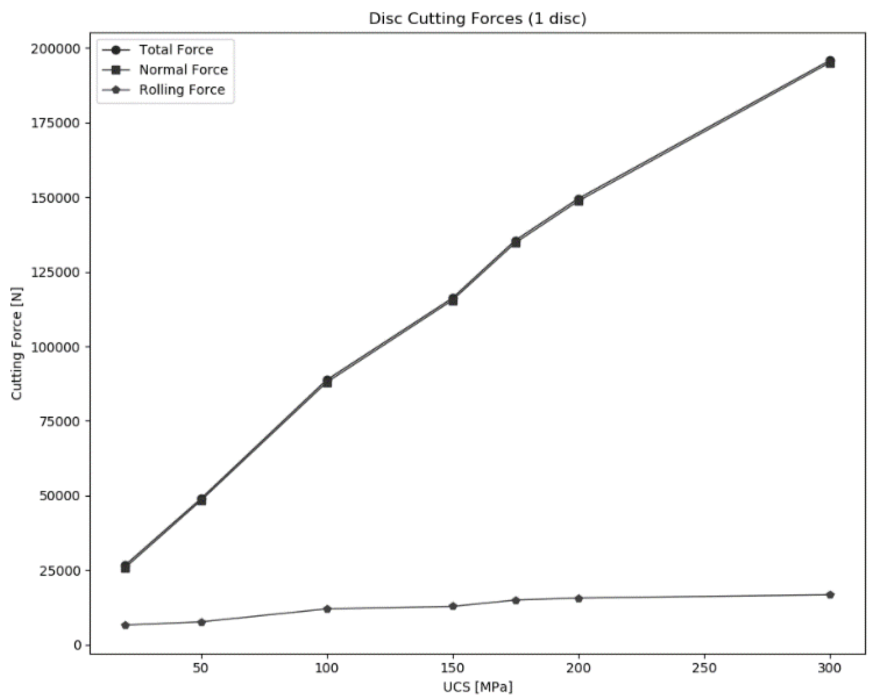

Figure 3: Required cutting force of disc tool *(Rostami, 1993*

The fact that tunnel boring machines and hard rock miners can penetrate hard rock zones is opposed by very high forces compared to roadheaders - even in soft rock. These results clearly show that the use of these technologies requires machines with the appropriate power and mass and any anchors or supports to be able to counteract the reaction forces.

Challenges

As described in the previous section, the economic efficiency of mechanical mining methods is limited by the strength and abrasiveness of the rock to be loosened. As already mentioned, the excavation process of mechanical tools requires high forces, which in turn act on the machine as reaction forces. During the mining process, the interaction between the tool and the rock generates forces that must be lower than the traction forces of the machine. Depending on the undercarriage (type and material) and the subsoil material, different drag conditions result. (Kunze, Göhring & Jacob, 2012)

Underground, rubber tires or caterpillar tracks are typically used as undercarriages of tunnelling and mining machines. As part of the EU H2020-ROBOMINERS project, other concepts for locomotion of robots in harsh environments were considered. Findings from this work showed the great potential of screw wheels as propulsion system. ***Figure 4*** compares the traction forces of the three variants mentioned above for a machine/robot with a total mass of 1500 kg. These traction forces were determined according to (WPFX / MacAllister, 2017; Cole, 1961) and graphically prepared for different subsurface materials.

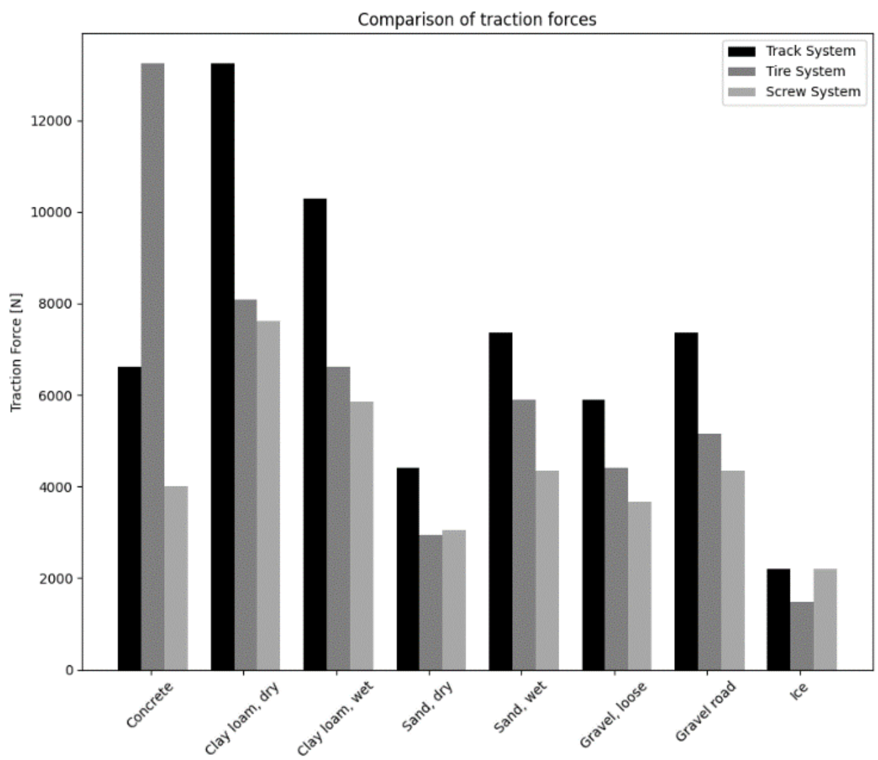

Figure 4: Traction forces of specific propulsion concepts depending on the surface material

In general, crawler tracks have the greatest traction forces, rubber tires have greater traction only on concrete, and screw wheels do not show a direct advantage over the other two drive types in any application.

However, worm wheels can be used in a more versatile manner and can thus increase the flexibility and mobility of a machine/robot. A symmetrical arrangement of an even number of worm wheels in relation to the base body of the machine/robot allows firstly a direction- and position-independent use and secondly the traction forces can be significantly increased by applying an additional gripping force with the help of the worm wheels (***Figure 5***).

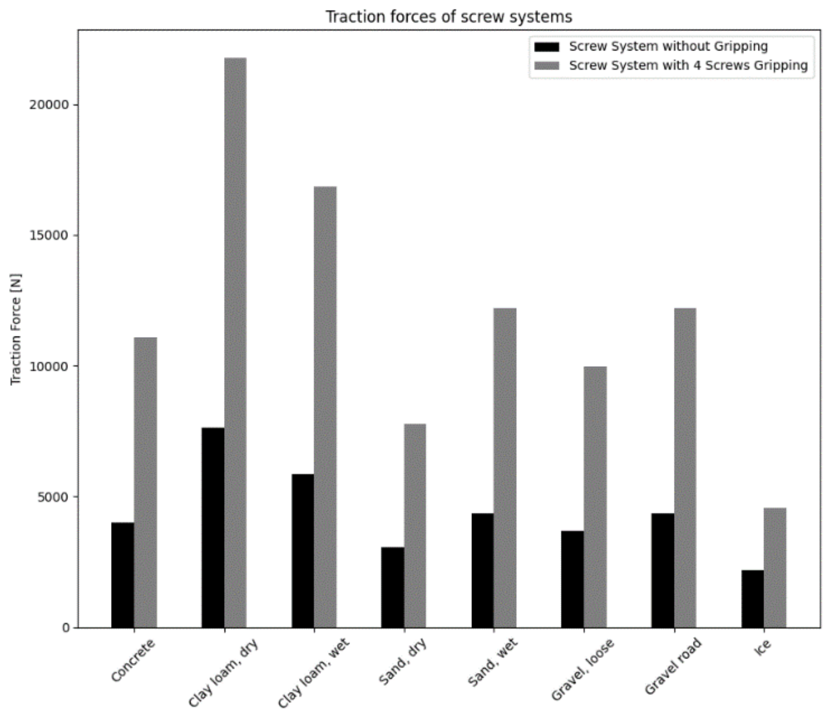

Figure 5: Traction forces of screw propulsion system with and without additional gripping force

Selection of alternative excavation technologies

In order to assess the applicability of the mining methods under consideration, they must be classified and roughly analysed in advance. In general, mining methods can be divided into: Drill and blast, mechanical, alternative and combined excavation methods, see ***Figure 6***. (Sifferlinger, Hartlieb & Moser, 2017; Berner & Sifferlinger. 2020; Vogt, 2016; Bilgin, 2013)

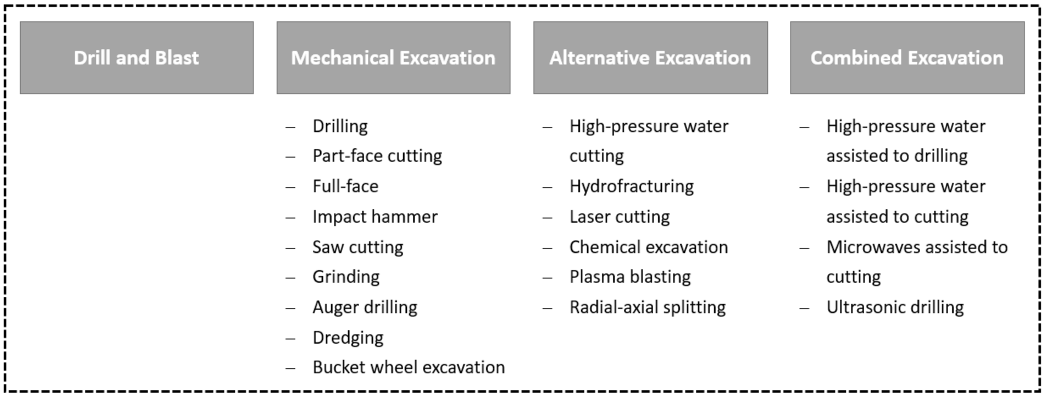

Figure 6: Overview of excavation methods

In (Berner & Sifferlinger. 2020), these technologies were investigated, analysed and evaluated according to selected criteria. Many of these methods are used for extracting raw materials or for tunnelling, but not all of them are economical in a small scale. First, the following characteristics are evaluated as imperative for future mining tools of small, mobile mining robots:

- The ability to continuously excavate material.
- The ability to create tunnels for the machine/robot's own locomotion.
- Limitations (compressive strength and abrasiveness of the rock to be mined, etc.).

Drill and blast is one of the most commonly used tunnelling and excavation technologies due to its general applicability in mining and tunnelling and its high production rate (especially for hard rock). Mechanical mining systems are at least as popular compared to drill and blast and have some advantages, such as safer operation, better selective mining capability, and continuous material removal. Alternative mining systems cover non-conventional mining methods. Main applications are precision tasks, pre-weakening of the rock to be mined (in combined mining systems) and tasks where environmental conditions do not allow conventional methods. Combined mining systems combine the advantages of mechanical mining systems and alternative mining methods. Auxiliary tools provide an additional energy input to pre-weaken the rock or reinforce the efficiency of the mechanical mining system. (Sifferlinger, Hartlieb & Moser, 2017; Berner & Sifferlinger. 2020; Bilgin, 2013)

The most commonly used mining methods in practice require a mechanical mining tool in at least one step. For this reason, it is necessary to study these systems in more detail. The high masses of the mechanical tools in relation to the mass of the machine/robot pose an additional challenge. Therefore, although characterized by high specific energies, alternative mining technologies are also considered since the required forces of the mining tool to penetrate the rock are comparatively low. (Berner & Sifferlinger. 2020) evaluated the applicability of the technologies based on the following parameters:

- Specific energy
- Excavation rate
- Thrust force/reaction force

Power, mass and the ability to absorb the reaction forces are identified as the most important parameters affecting the development of a small mining tool. In this case, the power and mass of the robot are assumed to be 40 kW and 1500 kg, respectively. The nature and the strength of the rock to be mined determine to a large extent the efficiency of the mining process and, above all, set strict boundary conditions for any mining system. In theory, the obtained values of specific energies and production rates seem reasonable and suggest a possible feasibility of a given technology. However, these results do not indicate practical feasibility. In reality, the machine/robot must generate the forces required to penetrate the rock - or the other way around - deal with the reaction forces acting on it. Usually, the reaction forces are counteracted by the high mass of the machine and, depending on the application and design, by additional anchoring mechanisms.

As discussed above, even the minimum cutting forces of full-face cutting technologies, which occur when mining very soft rock, exceed the capacities of the robot. Part-face cutting methods can only be used for soft rock material. Hydraulic and hydrostatic mining methods can be used to cut harder rock, although alternative methods have higher specific energies and lower production rates. High-pressure water jets reduce the cutting forces required by mechanical mining methods, but also require higher energy inputs. At this scale, drill and blast is the only remaining option for hard rock mining due to the low forces of the drilling process and the high efficiency of blasting. Technical feasibility is of secondary importance at this step and will be covered in prospective activities. Due to the comparatively low forces of alternative mining methods, they have a high potential for use in future mining robots.

RESULTS AND DISCUSSION

Drill and blast as well as hydraulic and hydrostatic mining methods each use a drilling tool in the first step of the mining process to create the boreholes. In practice, different types of drilling tools are used depending on the application. The great advantage of drill systems is the comparatively low feed forces required for the drilling process. Hydraulic and hydrostatic mining methods are use a drill as the primary tool and use the hydraulic pressure of fluids as the secondary mining tool. A conceptual idea of this mining method and the associated simulation methodology are presented. In the first step, concepts of various drill systems for a robot (40 kW power and 1500 kg dead weight) were developed, which are operated hydraulically or water-hydraulically. ***Figure 7*** shows the following concepts: a) hydraulic tophammer with chain feed, b) water-hydraulic down-the-hole hammer with chain feed, c) water-hydraulic rotary drill with feed cylinder, d) water-hydraulic rotary drill with feed cylinder and material collection filter.

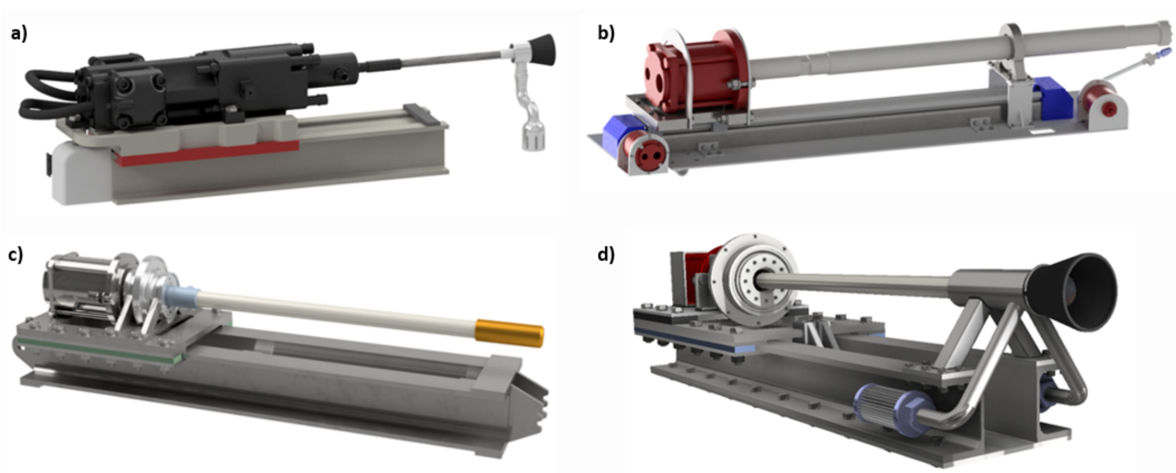

Figure 7: Drilling tool concepts

In the next step of the hydrofracturing process, an overpressure is created inside the boreholes by a fluid which initiate cracks in the rock body. The degradation process is simulated using the discrete element method in order to draw conclusions regarding the applicability and efficiency of the methods. In order to represent the rock realistically, the material parameters were calibrated in the first step by comparing them with the results of two laboratory tests. The compressive strength of the rock is determined by a uniaxial compressive strength test (UCS test) and the tensile strength is defined by an indirect tensile test (Brazilian Tensile Strength Test - BTS test). These two tests were simulated by DEM simulations and the material parameters were calibrated to represent the material behaviour up to failure. Subsequently, a simulation methodology was developed to investigate the effects of pressurized boreholes on the surrounding rock and the ability of fracturing the rock. The aim of these simulations is to make statements about critical borehole depths as well as distances and to define threshold values for hydraulic pressures within the boreholes. In the first step, crack initiation and crack propagation phases could already be mapped successfully. Furthermore, simulations with different hydraulic pressures were performed with already calibrated materials and influences of the pressure (up to 120 MPa water pressure) on the failure of the rock could be discovered. ***Figure 8*** shows the simulation process of a hydraulic degradation process.

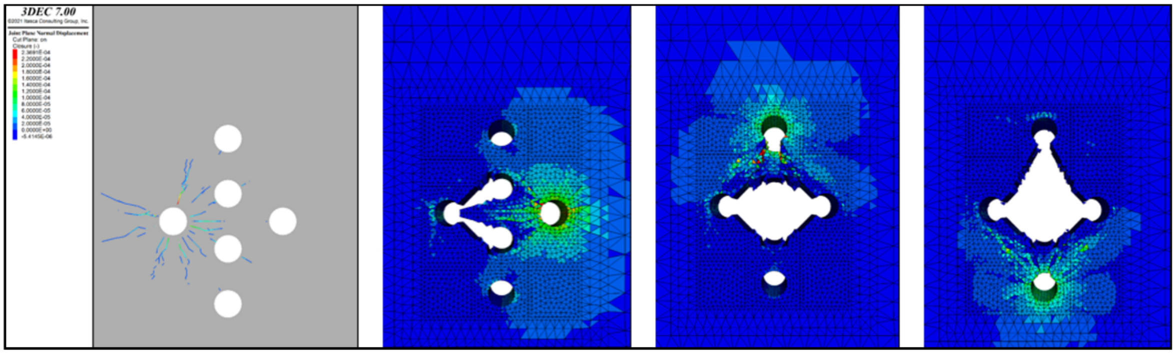

Figure 8: Simulation of hydrofracturing excavation technology

On the basis of the obtained results from different simulations with various borehole layouts, rock strengths and water pressure levels, a concept of a small-scale hydrofracturing tool will be designed in the future.

CONCLUSION

Using small-scale mining robots as excavation machines in the mining industry poses several challenges as a result of the combination of light weight and low power. Scaling down conventional excavation tools is a very limited solution and potential is seen only in very soft rock conditions. There will be a need of alternative excavation systems to decrease the mechanical forces required for extracting material. Specific energy of alternative excavation systems is generally much higher than of mechanical excavation systems, which demands highly efficient tools by implication. Additionally, a mining ecosystem entirely operated by robots includes numerous other important tasks besides the excavation process. Exploration, navigation, crushing, conveying, roof supporting, maintenance and other auxiliary tasks.

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