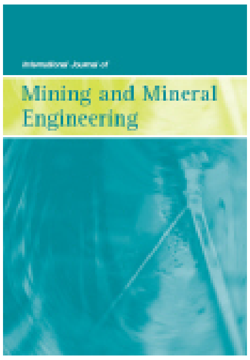

International Journal of Mining and Mineral Engineering

ISSN online: 1754-8918 - ISSN print: 1754-890X
https://www.inderscience.com/ijmme

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DOI: 10.1504/IJMME.2023.10056895

Article History:

Received:	02 August 2022
Last revised:	03 March 2023
Accepted:	21 March 2023
Published online:	20 June 2023

Enhancement of efficient coal fragmentation through technological advancement

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Abstract: Rapid technological advancements, including automation, digitisation, and electrification are having a significant influence on the mining industry. From exploration and geological modelling through equipment, operations and maintenance, and logistics and transportation, information technology is being used at every stage of the mining value chain. These new technologies can capture the information component of each unit of drilling and blasting operations accurately. To achieve drilling and blasting results that best fit the needs of the operation, the capacity to use information produced during these operations, as well as providing feedback loops for factual assessment is critical. Several technologies that can have a positive effect on drilling and blasting operations and pave the way for a unified approach to drilling, blast design, and blasting implementation are presented in this study. Some of the key issues, solutions and the various outcomes achieved during drilling and blasting in coal mines around the world are reported. To draw light on the advantages of technology, the major developments in drilling and blasting including utilisation of GPS aided drill rigs, intelligent drilling and charging, usage of blasting optimising software and laser technology for drilling which largely improve recovery and safety in coal mines are discussed.

Keywords: coal utilisation; information technology; automation; digitisation; electrification; fragmentation.

Reference to this paper should be made as follows: Said, K.O., Onifade, M., Shivute, A.P. and Adebisi, J.A. (2023) 'Enhancement of efficient coal fragmentation through technological advancement', *Int. J. Mining and Mineral Engineering*, Vol. 14, No. 1, pp.69–94.

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1 Introduction

The mining industry is known to be a volatile industry entailed with numerous unforeseen and dynamic variables such as fluctuating mineral prices, ore grades, and concentrations. Additionally, the sector has a history of being destructive thereby; it has incessantly faced environmental and social responsibilities amongst communities which affect the profit margins (Kolesnikova and Kovalchuk, 2021). Despite the enormous contributions that emanate from mining that are crucial for human survival such as the production of building materials and minerals for processing medication, the sector is compelled to adopt better techniques to improve production efficiency and reduce environmental and safety risks to inject sustainability into the whole value chain (Sánchez and Hartlieb, 2020). To equip the mining sector with operational security, the sector needs to adopt innovative technologies to cut down operation costs, reduce safety risks and environmental pollution (Hermanus, 2017).

Drilling and blasting are crucial mining operations that allows the fragmentation of rocks to smaller manageable sizes for loading, haulage, processing, and transportation to the market. Proper designing of drilling and blasting systems is paramount in mining operations as this step produces materials for subsequent operations (Isheyskiy and Sanchidrián, 2020). Other than achieving the desired fragment size of the ore, the process needs to be economical and safe for both the miners and the surrounding environment. Drilling and blasting can pose serious financial, environmental, and safety risks. Poor drilling and blasting can result in boulders which may require secondary blasting, thereby, negatively impacting the profit margin (Agyei and Owusu-Tweneboah, 2019). Many studies have demonstrated that problems with rock mechanics and geoengineering are particularly specific to a given site and are characterised by limited data and understanding (Lawal and Kwon, 2021). Because it does not require any prior knowledge of the type of relationship that exists between the predictors and the predicted variables, AI is a viable technique for simulating such a relationship. Rock fragmentation sizes have also been predicted using machine learning (ML) techniques like classification and regression trees (CART), artificial neural networks (ANN), ANN optimised with the artificial bee colony (ANN-BC), ANN optimised with the fire fly algorithm (ANN-FA), and multiple linear regression (Lawal, 2021). In another study by Lawal et al. (2022), the response surface method (RSM), ANN, regression tree (RT), and gene expression programming (GEP) were used to predict more accurate models for the mean fragment size of rock. The study found that based on the RSS, which is an optimal statistical criterion in model selection, ANN performs better, followed by RT and GEP.

Safety risks from a poorly executed blasting can result in excessive ground vibrations, flyrocks, airblasts, and noise. This may harm miners and compromise surrounding structures, leading to failure (Kiani et al., 2019). Conventional drilling and blasting methods produce high energy quantity that releases gas and shock waves together with light, heat, and sound. Whereas the energy should be used to break down the rock mass, some energy is ineffectual and causes disastrous impacts to human lives and the surrounding environment (Jiang et al., 2017). In other instances, the explosive energy is lost leading to unsuccessful blasting operation due to poor stemming. To overcome such drawbacks, studies have reported the suitability of various stemming materials for various blasting operations as indicated in Table 1.

In coal mining industry, the sector is challenged by numerous setbacks stemming from both its inherent properties which make it susceptible to fires and extrinsic operation factors which pose negative impacts to the environment. Having drilling and blasting as one of the key rock breakage techniques, the coal mining industry has suffered from myriad of challenges due to incompetent techniques used which has negatively influenced safety, operation efficiency and financial base of the companies.

To deliver stripping of overburden to expose coal deposit, miners utilise drilling and blasting method for rock fragmentation. Previous studies have reported that this technique is widely preferred due to its effectiveness and convenience as more coal face can be exposed in a cycle. However, the haphazard usage of explosives damages coal deposits, thereby negating the benefits of blasting (Kanchibotla, 2000). Some coal deposits have complex geological formations and elevated gaseous contents which require customised drilling and blasting techniques to avoid catastrophes (Cheng, 2021).

Table 1 Summary of various stemming material suitable for various blasting operations

Category	*Stemming material*	*Prowess*	*Weakness*	*Reference*
Conventional blasting	Gel	Good drill hole blocking potential, reduces production of dust and noxious gases	Complex loading operation and takes time to set and harden	Wang (2007)
	Surfactant	Good drill hole blocking potential, reduces production of dust and noxious gases	Expensive	Jin et al. (2007)
	Blend of clay, sand and water	Good drill-hole confinement abilities	Bulky transportation, expensive operational cost, and lengthy loading time	Choudhary and Rai (2013)
	Rock powder	Low operational cost with moderate drill hole blocking effect	Bulky transportation and lengthy loading time	Sharma and Rai (2015)
	Water absorbing rubber	Cheap and easy to use	Poor drill hole blocking effect	Wang et al. (2015)
Air-interval blasting	Gas injection	Low production of dust and noxious gases	Produces very low friction, therefore, cannot be used alone	Kang (2006)
Large drill hole blasting	Inorganic quick setting	Cheap with relatively good blocking effect	Must be complimented with pressure and water stemming	Cevizci and Ozkahraman (2011)
	Organic quick setting	Cheap with relatively good blocking effect	Must be complemented with pressure and water stemming	Marinho et al. (2017)
Special diameter drill hole blasting	Spherical plugs	Moderate blocking effect and easy to use	Requires preloading of drill hole and stemming twice	Jenkins and Jenkins (2001)
	Spherical burst plug	Moderate blocking effect and easy to use	Complex architecture	Shann (2002)
	Combination plug	Moderate blocking effect and easy to use	Complex architecture	Sazid et al. (2011)

For example, poor blasting practices in the Landau colliery led to blasting accidents in 2009 which resulted to casualties and damage to the environment due to hot-holes in South Africa (Rakoma, 2013). Studies have also reported coal losses leading to poor ore recovery due to poor blasting practices which impose financial losses to investors in Australia (Goswami et al., 2008). Additionally, blasting in coal mines have been reported to suffer from attaining optimised detonation energy when the performance of various plugging material in coal mines using sand, debris and clay were analysed in China (Yang et al., 2018). To expose coal face for mining, it is imperative to employ efficient drilling and blasting methods that can break larger volume of rock per cycle. However, the conventional techniques have been reported to have low drilling efficiency and blasthole utilisation efficiency (Wang et al., 2017).

To overcome such challenges, mining companies must adopt better drilling and blasting methods using advanced techniques which can aid the miners to select proper drilling and blasting designs. Advanced techniques guide the miners to implement proper drilling and blasting by recommending optimum parameters such as the number of drill holes, angles of drill holes, spacing, burden, types of explosives, and direction of flow (Rao et al., 2018). This paper presents the benefits of using technological inventions in mining and subsequently covers the recent techniques used in drilling and blasting such as usage of global positioning systems (GPS), laser technology, intelligent blasting, and software. Furthermore, this study presents future drilling and blasting techniques which will revolutionise coal mining fragmentation.

2 Impact of technological innovations in the mining sector

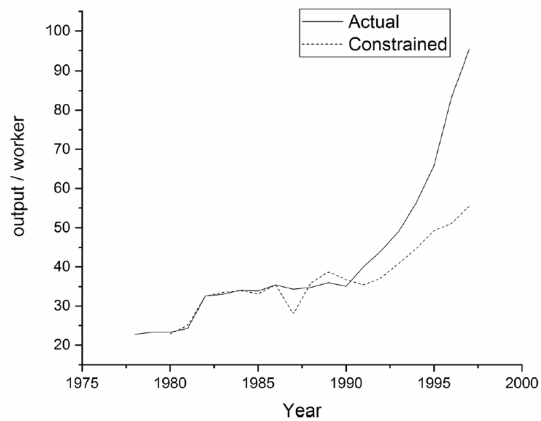
To meet the ever-rising demand for minerals around the world, the mining industry has adopted technological innovation to improve production, safety, and cost of operations. Such technologies include solver extraction and electro-wining in hydrometallurgical production which has largely contributed to copper production in the USA (Hamit and Tilton, 2000). Similarly, the production of coal was largely boosted by the invention of continuous miners for underground coal mining and draglines and bucket wheel excavators for surface coal mining. The invention of flashing and bottom blowing furnaces has tremendously impacted energy reduction in smelting operations, thereby saving on operational costs (Hamit and Tilton, 2000).

To better comprehend the relevance of adopting better technological innovations in the sector, it is crucial to analyse the impact it has on labour productivity. One approach to analysing the success of any technological innovation is by assessing whether production increases with a given workforce or the ability to reduce personnel and still meet the required target through automation. However, any mine’s productivity can be affected by other natural factors such as reduction of ore grade requiring more volumes of materials to be mined or even occurrence of mineralogy in deep zones requiring complex designs for extraction (Joaquín et al., 2010).

To better understand the effect of innovation on mining productivity, several studies have reported different findings. The study by Tilton and Landsberg (1999) reported the relevance of innovation and technology in mining while analysing the drop and recovery of the USA copper mining situation that happened from the 1970s to 1980s. Findings from the study recognised usage of better material handling systems and processing techniques as key to the revival of the copper sector. These included the usage of modern drilling wagons, computerised scheduled trucks, in-pit crushers and conveyors for material handling and solver extraction, and electro-winning techniques for processing copper. However, this study failed to account for the impact of new deposits on production during the period under study.

The study by Garcia et al. (2001) analysed the increase of labour productivity of copper in Chile from the year 1978 to 1997 as presented in Figure 1. The results indicated that utilisation of new mining technologies attributed to about a third of the production rate. Further analysis indicated that 100% of production growth was experienced in the years 1978–1990 while extraction from a new Escondida mine contributed to the labour production from 1990 to 1997 (Garcia et al., 2001).

Figure 1 Labour productivity in Chile copper industry showing actual and constrained production

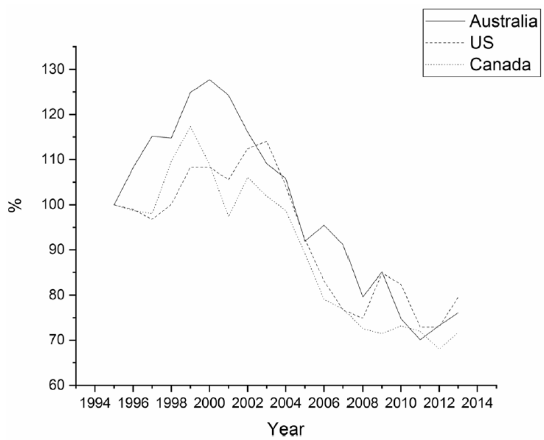


Source: Garcia et al. (2001)

Furthermore, a study by Joaquín et al. (2010) reported that innovation, new technologies, and good managerial skills have been instrumental in improving copper production from Peru and Chile. However, despite the introduction of technology in mining operations in the 1990s, it is important to note that production increment is safely secured. Taking the example of Chile, it is worth noting that copper production took a plummet in the year 2005, a situation that was similarly experienced in Canada, Australia, and the USA in the early 2000s as illustrated in Figure 2. The reduction of copper production in the reported countries was majorly due to natural and economic factors. Such natural factors include reduction of ore grade, an increase of haul distance as mining progress, increase of stripping ratio in deeper zones, and geotechnical issues which all negatively impact the profit margin (Fernandez, 2021). Therefore, whereas economic and natural factors are beyond human control, proper mining technology must be adopted to boost production. Adopting technological innovations is a crucial aspect in ensuring that mining companies remain competitive in the sector to overcome the existing hurdles and be able to exploit complex deeper deposits (Nanda, 2020).

Other than improving production through the invention of better mining technologies, innovations have enabled the tapping of ore zones that would have been technically impossible to mine using conventional techniques. Such inventions include pre-conditioning of rock mass through hydraulic fracturing, confined fragmentation, or a hybrid of both techniques to enabled mining of deeper ore zones in higher stress environments. To improve on safety and reduce disasters especially in underground mines, technology has focused on automation and robotics to send machinery in risky missions which were previously done by miners. Furthermore, abiding by environmental policies and addressing problems of surrounding mining communities are key necessities of sustaining social licenses to operate. These technological innovations have been focused to develop cleaner and eco-friendly techniques in the entire mining value chain including exploration, development, mining, processing, selling, and reclamation (Upstill and Hall, 2006). Despite the proven advantages of technology in mining, the coal mining industry continues to suffer from various operational problems such as coal fires, noxious gases emissions and poor fragmentations which does not only negatively affect the profit margin and pollute environment but also, exposes miners to mine safety hazards.

Figure 2 Labour productivity in selected mining countries from the year 1995 to 2013



Source: Fernandez (2021)

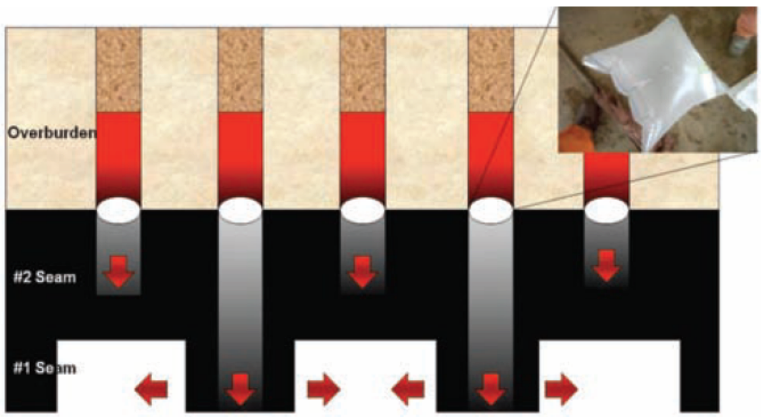
3 Trends in coal drilling and blasting

Due to the ability of coal to undergo self-heating, its process of drilling and blasting has been immensely affected due to hot-holes which result into premature detonation of blastholes. The study by Rakoma (2013) analysed the causes of Landau colliery blasting incident that occurred in 2009 in South Africa. Whereas previous mining took place in virgin areas, the Landau colliery expanded to allow extraction of coal above old underground workings that were exploited using room and pillar method. However, whereas the underground coal was successfully removed, the process of mining exacerbated coal self-heating due to increased exposure to oxygen in the air. Furthermore, several sink-holes and hot-holes emerged at the roofs, thereby, affecting the mining of upper seams using surface mining methods. The study reported that the surface coal mining method entailed rock fragmentation using air-decking method which highly compromised safety of personnel due to premature detonation as indicated in Figure 3. To avoid this, effort was directed to utilise manta-locks (as indicated in Figure 4) to confine the charge but the techniques produced poorly fragmented coal material. The study simulated drilling operations in excel and reported several causes for poor fragmentation which included: drilling deviation, tie-in sequencing, high soft to hard ratio of 1.62 to 2 and high spacing to burden ratio of 1:2 (Rakoma, 2013).

The study by Goswami et al. (2008) reported low coal recovery and high damages in Ensham mine in Queensland Australia due to the fragile nature of coal deposits and complex geological conditions. To improve on production, drilling and blasting was utilised using shallow throw method and post-strip blasting underneath. Additionally, baby-decking was used in tandem with a large buffer material in front of the coal face.

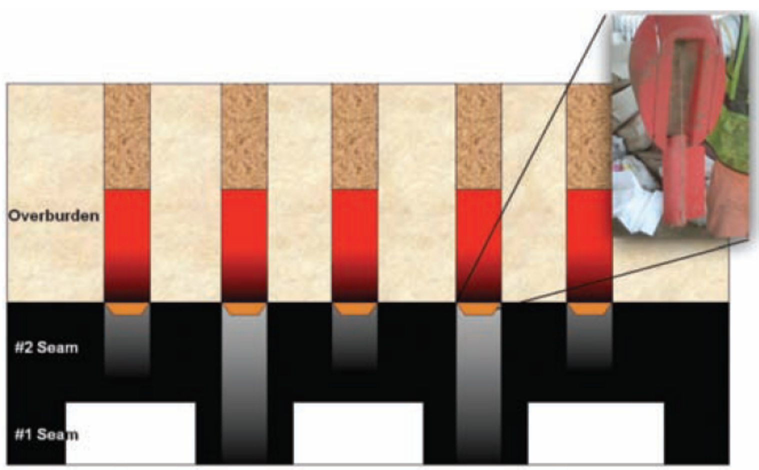
Despite the efforts to employ the methods, the study indicated no improvement in coal fragmentation due to the presence of complex geological features, coal seams covered with weaker buffer material either at the top or bottom, presence of water, inaccurately designed blasting pattern, poor blasting timing and poor selection of types of primer and explosives. To overcome such drawbacks, the study utilised Stratablast to design and optimise drilling and blasting patterns. Implementation of such technology significantly improved recovery and reduced coal losses (Goswami et al., 2008).

Figure 3 Gas bag blasting technique (see online version for colours)



Source: Rakoma (2013)

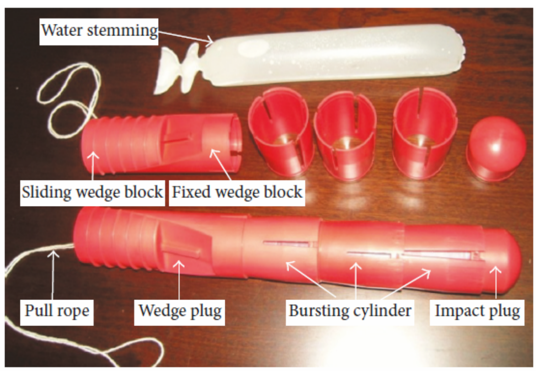
Figure 4 Manta lock blasting (see online version for colours)



Source: Rakoma (2013)

Underground coal mining is known to be susceptible to rock burst due to pressure build up. The study by Yang et al. (2018) reported on the need of drilling and blasting to relieve rock pressure. To attain optimum rock fragmentation output, the study reported on the relevance of hole-blocking to contain blasting pressure and conventionally done using clay as a stemming material. However, such technique is known to be laborious in terms of manpower and time needed for hauling and loading of the clayey material. To overcome the drawback of stemming using clay, study by Yang et al. (2018) developed an environmental friendly blasting hole-plug for stemming (cheaper and more efficient in terms of stemming, loading and transportation) made from polyethylene as indicated in Figure 5. Testing of the plug at the laboratory indicated that it had 14%–16% more motion time, 19%–54% less motion and 22%–66% less compression compared to clay stemming under similar conditions and impacting energy. The study reported that the plug can contain more pressure of greater than 410 J than clay material that exits at pressures of about 340 J. Hence, the developed plug could provide better blasting performance in coal mining and produce better fragmentation output. Furthermore, the study reported an industrial test to compare the two stemming material and indicates that the plug reduces unit explosive usage by 24%, offers faster footing driving cycle by 8.9%, improves blasting efficiency by 4.8%, decreases dust production by 23.6%, and lowers noxious gases production by 11.0% (Yang et al., 2018).

Figure 5 Polyethylene blast plug (see online version for colours)



Source: Yang et al. (2018)

The study by Wang et al. (2017) reported the status of excavation of coal roadways in China which is achieved using blasting millisecond in a 2 m drill hole depth. The study indicated that blasting efficiency in coal mines is mostly affected by geological composition, blasting design and footage per cycle which potentially result to failed detonation and consequently lowers the development rate in underground mines. The study recommended the implementation of a parallel cut blasting using a more rapid drilling jumbo with the ability to drill auxiliary drill holes of about 38 mm diameter as well as create solutions for large diameter blastholes having diameter of 120 mm and 3m depth to improve on it. The study suggested an optimised drilling and blasting design to be used in conjunction with the drilling machinery having eight small drill holes parallel to big drill holes to commence blasting. The simulation of this technology has proven to have faster drilling and blasting cycles, thereby, allowing development of underground mines. The technology can also drill at 360 degree at various angles, thereby aiding the process of cutting holes next to major drill holes. Application of the technology in coal mine tunnelling has increased utilisation to about 90%, reduced drilling of excessive 5–10 holes, usage of detonators and explosives to more than 0.2 Kg/m^3 (Wang et al., 2017).

The study by Kanchibotla (2000) reported that despite explosive energy being crucial in rock fragmentation; excessive usage of such material poses a serious risk in damaging coal seams which ultimately decreases rate of recovery. To establish the optimum usage of explosives in open cast mines, the study monitored the performance of various quantities of explosives on rock fragmentation. In the study, the study areas were divided into three sections whereby all drillholes in area 1 were drilled having 1 m stand-off gap, all holes in section in 2 were drilled into the coal seam and were backfilled up to 2 m with gravel and all drill holes in Section 3 were drilled to 0.3 m above the coal seam and were initiated using baby decking. To monitor the performance of each section, geophones and pressure gauges were installed strategically in monitoring holes to assess the magnitude of stress waves and gas pressure on coal seams. The study reported that three mechanisms are involved in damaging of underlying coal seams: induced stress waves, gas pressure and burden movements. Additionally, the results indicated that magnitude of coal seam damage is dictated by standoff distance from explosive deck, initiation system, properties of coal seam and underlying coal seams. Additionally, high speed photography indicated that initiation through baby decking reduced probability of coal seam damage which was further supported by coal roof survey. The study indicated that baby decking priming significantly reduces seam damaging as compared to bottom priming (Kanchibotla, 2000).

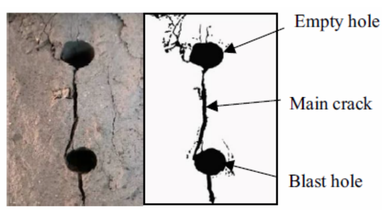
The study by Cheng (2021) reported the importance of presplitting in solving the issues of gas outbursts and low recovery rate in broad coal seams. The study analysed the application of presplitting in a coal seam having 12 m thickness, hardness coefficient ranging between 2–3 and gas content of 9.43 m^3 per ton to solve this problem. To reduce environmental pollution due emission of toxic gases, the study attempted to capture trapped gases in coal seams through a technological roadway which was developed in the coal seam parallel to the working face and linked to machine and air roadway. Drill holes were arranged from 2.5 m high technology roadway on both ends, and 1 m above the floor. The study reported that permeability in coal increased after blasting while the coal mass decreased due to change in stress due to loose blasting. Based on theory of explosion, the analysis indicated that whereas gas quantity reduced, there was an increase in rate of recovery. The average gas concentration increased from 9.6% to 35.1% while coal recovery increased from 75 to 113 (coal yield per month/$10t^3$). Therefore, the study proved that presplitting in coal blasting does not only increase coal permeability but also helps in trapping gas that would otherwise be released to the atmosphere. Furthermore, the loosening of coal helps in redistributing of stress, reduces dragging of gas drainage and improves safety in coal mining operation (Cheng, 2021).

To improve coal mining production, Dill (2016) analysed the impact of utilising directional drilling for removal of overburden. The study used AutoCAD to design the drilling pattern of 25 drillholes and geotechnical analysis followed to determine the hole stability through modelling. A drill rig with the potential of making a 90 degree turn in 25 feet was utilised to drill into the overburden. The results indicated that directional drilling in coal mining is advantageous as it saved up to 13% of drilling and blasting cost (Dill, 2016).

Based on the risk of blasting in weak coal-rock pathways, study by Ding et al. (2020) analysed the effect of double-wedge cut blasting techniques to optimise blast hole design using medium drill holes. To determine the effect of cut blasting mode on the blasting efficiency of weak coal rock, the study designed three blasting programs by altering the arrangement of cut holes, design and depth of blast holes. Three hole cutting techniques were used including parallel, ordinary wedged and double wedged. Analysis of the results indicate that double wedged cut despite having no residual holes, it presented a good roadway forming effect and shorter cycle time to achieve 2 m. Furthermore, the results indicated that the double wedges cut technique is preferable for blasting medium lengthen holes having an efficiency of 86.9% compared to other cutting techniques (Ding et al., 2020).

Pan et al. (2020) analysed the performance of carbon dioxide presplitting blasting on coal seam and rock mass with holes permeability and gas drainage. The study utilised empty holes to conduct CO_2 presplitting in coal and rock mass whereby VIC-3D was utilised for monitoring changes in surface displacement while the amplitude wave of blasting waves was captured using ultrasonic waves. The study analysed attenuation coefficient, internal crack damage and crack propagation in coal and rock mass due to the empty hole. Analysis of the results indicated that radial tensile stresses is developed from superposition of compressive and reflective wave from blasting leading to the development of a relatively flat crack between blasthole and empty hole. In addition to that, when stress and attenuation reach their maximum value, a major crack is formed leading to destruction of the coal seam and rock mass as indicated in Figure 6. Finally, the major crack was formed at 0.13 seconds and the maximum energy consumed at 0.18 seconds, giving a linear relationship between energy and stress. The study proved that the empty hole offers good guidance in propagating cracks on both coal seams and rock mass as well as improves permeability of coal (Pan et al., 2020).

Figure 6 Crack development



Source: Pan et al. (2020)

To reduce hazards due to coal and gas out bursts, study by Yang et al. (2020) developed a new blasting injection integrated (BII) technology as illustrated in Figure 7. The study utilised a series of de-stressing blasts to release stress close to the mining face and reduce the stress peak from the mining face. Generation of cracks due to blasting does not only promote connection between pre-existing cracks but also aids in the reduction of gas from the mining face. Thereafter, water was injected into the coal seams through blast holes for improvement of coal plasticity and decrease rate of gas diffusing out through bursts. The study entailed setting a series of instruments including hole packers, transporting and safety instruments. The implementation of the BII technology in an active mine is useful for reliving stresses in active coal face longitudinally by approximately 5 m and gas emission increased by two within 30 minutes after de-stress blasting. Additionally, injection of water volume after distressing rose 25 times more than the unblasted section and gas quantity in return pathway from 0.58% to 0.36%. Furthermore, dust concentration was also reported to have drastically reduced, indicating that the BII technique is suitable for limiting coal and gas out-burst potential (Yang et al., 2020).

Table 2 Trends of technology to enhance drilling and blasting in the coal industry

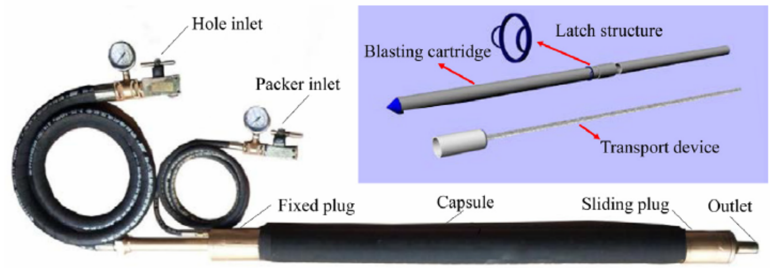
Country (case study)	*Challenge(s)*	*Cause(s)*	*Solution(s)*	*Results*	*Reference*
South Africa (Landau colliery)	1 Premature detonation due to hot holes	1 Coal oxidation	1 Manta-locks	Poor fragmentation of coal seams	Rakoma (2013)
	2 Production of boulders	2 Drill holes deviation	2 Adjusting spacing to burden ration to 1.15	Improved fragmentation by 48%	
		3 High soft to hard ratio 1.16:2	3 Blasting within 24 hours after drilling		
		4 High spacing to burden ratio of 1:2	4 Bore tracking		
Australia (Ensham mine)	1 Coal loss	1 Fragile coal seams	1 Stand-up blasting	Coal damage and loss	Goswami et al. (2008)
	2 Coal damage	2 Complex geological conditions	2 Throw blasting in 80% of overburden followed by post strip blasting.	Expensive operations and increased cycle time	
			3 Baby-deck throw blasting simulation	20% cast to final spoil	
			4 Baby-deck throw blasting with buffer simulation	24% cast to final spoil	
			5 Bottom stand-up blasting simulation	17% cast to final spoil The implementation resulted to improved recovery	
China (Yungang Coal Mine)	Stemming using clay	The material is bulky therefore making the work laborious in transporting, loading and manpower.	Development of environmentally friendly polyethylene stemming plug	1 Increased motion time from 14% to 63%. 2 Increase in end movement from 19% to 54%. 3 Improved compression deformation from 22% to 66%. 4 Improved explosive consumption by 24% and blasting efficiency by 4.8%.	Yang et al. (2018)
China	Incomplete blasting due to unexploded dynamite	Complex geological and blasting factors	Using drilling jumbo with the potential of drilling auxiliary, large diameter and centre deep hole.	1 Better cutting holes 2 Improved drill hole utilisation	Wang et al. (2017)

Table 2 Trends of technology to enhance drilling and blasting in the coal industry (continued)

Country (case study)	*Challenge(s)*	*Cause(s)*	*Solution(s)*	*Results*	*Reference*
Australia (Warkworth)	1 Coal damage 2 Low coal recovery	Excess explosive energy	Baby decking 2 m gravel back fill Drilling to marker band	29.21% cast and 4% coal loss 29.17% cast and 13.30 coal loss 27.51% cast and 9.10% coal loss	Kanchibotla (2000)
Chinese coal mine	1 Gas outburst 2 Low coal recovery	Low coal permeability	Deep hole pre-splitting blasting	1 Increased coal seam permeability 2 Better gas extraction 3 Safer and more efficient mining operations	Cheng (2021)
Montana Tech of the University of Montana.	Low coal recovery	Overlying overburden	Directional drilling	Reduced drilling and blasting cost by 13%	Dill (2016)
China (Xiayukou coal mine)	Poor blasting excavation	Complicated geological formation	1 Parallel cutting 2 Ordinary wedge 3 Double wedge	Double wedge has good roadway forming effect, shorter cycle time to achieve 2 m and efficiency 86.9%.	Ding et al. (2020)
Experimental study (University of Science and Technology)	Poor crack propagation	Geological formation	1 Empty holes to conduct CO_2 pre splitting in coal and rock mass 2 VIC-3D was utilised for monitoring changes in surface displacement while the amplitude wave of blasting waves was captured using ultrasonic waves.	The empty hole offers good guidance for propagating cracks on both coal seams and rock mass as well as improves the permeability of coal.	Pan et al. (2020)
China (Pingdingshan City)	Coal and gas outbursts	Gas and ground pressure	Blasting injection integrated (BII) technology together with water injection.	1 Emission increased by two within 30 minutes after de-stress blasting. 2 Injection of water volume after distressing rose 25 times more than the unblasted section and gas quantity in return pathway from 0.58% to 0.36%.	Yang et al. (2020)

The trends of technology used in the coal industry to enhance efficient drilling and blasting are presented in Table 2.

Figure 7 BII technology (see online version for colours)



Source: Yang et al. (2020)

4 Available new technology/modern drilling and blasting technology

An increase in global population is marked by a subsequent increase in mineral demand to sustain good living standards through the production of building material, minerals for medication, products for manufacturing automotive and communication systems amongst others. Additionally, the mining industry has faced challenges emanating from safety, environmental and social concerns, thereby driving the sector to seek more efficient, safer, and eco-friendly mining methods.

Execution of drilling and blasting is crucial in achieving the right fragmentation properties for subsequent operations such as crushing, processing, and haulage. To achieve a good rock fragmentation, suitable drilling, and blasting design must be developed which considers the rock mass properties as obtained from geological investigations. A successful drilling and blasting operation will not only produce required rock sizes by eliminating the need for secondary blasting but also reduce fly rocks, ground vibrations, and general environmental impact. Furthermore, it is paramount that mining companies adopt suitable drilling and blasting practices to ascertain that produced dust and gas from drilling and blasting does not pose any health or safety risks to the operators. Some of the key technological advances adopted in drilling and blasting operations in the mining industry are discussed below.

4.1 Global positioning system

GPS has improved the accuracy of drilling which contributes to better fragmentation and reduced safety risks during blasting. Using GPS technology, the geographical information system has been instrumental in analysing, capturing, storing, managing, and displaying drill and blasting data (Signh, 2000).

In a highly digitalised era, the use of GPS has aided in improving drilling precisions and addressing drilling challenges using efficient and cheaper approaches. The introduction of such advanced technology has slowly led to the elimination of stacking and human errors as experienced with traditional surveying systems. Drilling machinery can be integrated with various sensors which can enable digitisation and transmission of data to any location for analysis. An example of this includes the Intelmine High Precision Drilling System by Modular Mining Systems built using GIS whose functioning relies on digital blasting designs and onboard colour graphics consoles to generate the precise location of drilled boreholes. Every borehole can be surveyed as part of a drilling mission to generate 'as-built' data of holes in each location.

Cutting-edge drilling and blasting technology have also been developed by Aquila Mining Systems which monitors drilling efficiency, recognises material, and guides drilling machines for vertical and inclined drilling. The first component allows the operator to learn in real-time the drilling production and efficiency while the second component is equipped with vibrational sensors and pattern recognition elements for determining the type of rock being drilled. Lastly, the guiding component enables the driller to control the orientation of drilling in either a vertical or inclined position to enable drilling up to an accuracy of 1 cm. Having GPS embedded on the drilling rig, it automatically generated 'as drilled' blast hole data that can be transmitted to the blasting design system through a wireless system for reconciliation with the actual drilling.

Advancement in technology has allowed capturing of lithological data by the drill monitoring systems and assays from such drill holes are used to update geological models and generate quality control information for blasting and production. An example of this is the MineScape system that provides a platform for exporting geological information such as drill-hole locations, depth, and reference graphics to Aquila and DrillNAV GPS systems.

A coal mine in Indonesia increased its productivity and blasting efficiency by automating coal seam detection during its drilling operations. The mine utilises a mining sequence with through-seam blasting (TSB), which allows them to blast one or more coal seams at a time. Under normal circumstances TSB necessitates drilling to a set depth in the pit, to accurately pinpoint coal seams' depth, thickness and location in order to reduce any losses or dilution. The mine was heavily reliant on a single gamma logging tool to detect the coal seams, this limited them to manually logging one TSB location daily. This resulted in delaying the blasting process by 24 hours and subsequently making the drilling, charging and blasting process take an accumulated time of three entire days. Due to the loose of time during the TSB process, the mine prompted to automating the process by introduction ProVision system's drill hole stratification module by modular mining systems. This helped alleviate the 24 hour waiting period for manual logging and analysis thus increasing productivity (Modular Mining, 2020).

A study by Balamadeswaran et al. (2016) developed a GIS model for drilling and blasting to predict the impact of ground vibrations. The study measured lithological properties of the rock mass in different benches and determined blast-induced vibrations based on types of rock formations. Subsequently, a thematic map was developed to indicate blast-induced vibration levels for various rock formations integrating structural geological features using GIS. The thematic map proved as an effective tool for giving insights regarding the influence of rock properties on blast-induced vibrations in blasting designing to protect surrounding structures such as slopes and buildings (Balamadeswaran et al., 2016).

4.2 Laser technology

Increased demand for mineral resources has compelled mining companies to extract minerals found in deeper and harder rock mass formed over 1,000 years. Despite the oil and gas having advanced drilling techniques that have improved drilling efficiency; their performance suffers in harder formations due to lower penetration rate and weak drilling bit which consequently increase operation cost. Advancement in technology using laser technology has been proven to offer more powerful energy from more efficient rock breakage. Studies have reported the ability of laser technology to reduce mining costs due to greater transmission potential which produces a substitute to conventional drilling bits and blasting methods (Bharatish et al., 2019). Additionally, laser technology reduces drilling time through the elimination of rock contact and the need of replacing mechanical bits. Furthermore, studies have reported the advantages to include the formation of a melted rock wellbore lining that eliminates the need for steel casings (Jamali et al., 2019).

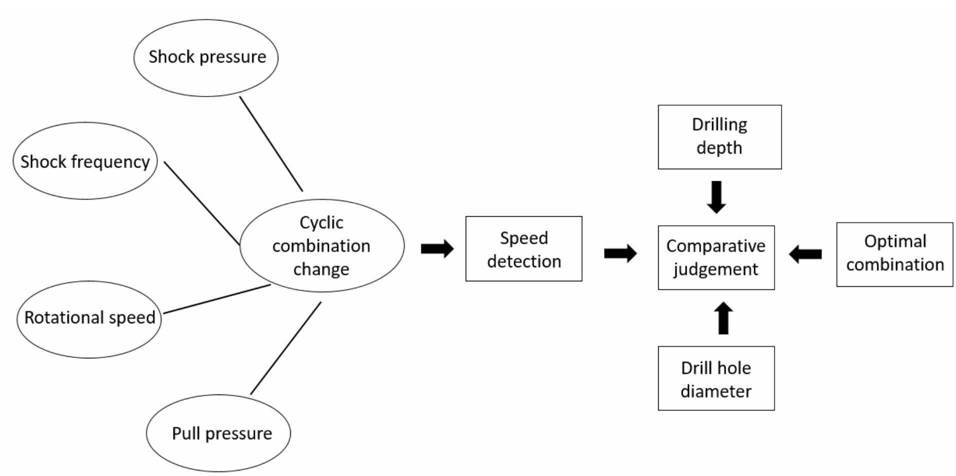
Laser technology has been reported to be the most effective drilling technology as it reduces the energy required to extract a unit mass of rock while increasing the penetration rate (Xu et al., 2002). Advanced laser technology has been reported to have sufficient power to spall melting and vaporise all rock types. Research by Jamali et al. (2019) studied the impact of thermal inducing drilling on various rock types which included sandstone, granite, and metamorphic quartzite. The rock samples were thermally treated using continuous waves (CW), pulsating laser beams, CW double line, and pulsating single line. The rocks were characterised to determine their initial properties and potential alterations after subjection to a laser. The study reported that laser jet drilling technology can easily transform the rocks into an easily drillable state, thereby easing the work of mechanical drilling. A scratching test was used to obtain rock strength, drilling strength, and toughness for each sample. Findings from the study indicates that thermal rock softening enables effective facilitation of combined laser mechanically assisted drilling technique with a higher penetration rate of the cutting tool with less torque, thereby consuming less energy. For example, the rock strength of granite was significantly reduced by 60% after CW lesser treatment while sandstone was reduced by 58% after CW and pulsating treatments. Quartzite being the hardest rock sample that could not be scratched before lesser treatment, the rock sample had lesser geo-material properties than granite after thermal inducement. Furthermore, the technique is cheaper as it increases the drill-bit life and reduces the drilling period (Jamali et al., 2019).

A study by Bharatish et al. (2019) reported the advanced transmission abilities of laser drilling technology which subsequently reduce mining operation costs. The study evaluated the impact of laser drilling variables such as laser power, frequency, assist gas pressure, and drilling time on rock samples including limestone, shale, and sandstone using 12 Kw carbon dioxide laser. Drilling of limestone used 46.14 KJ/mm^3 of energy having a penetration rate of 15.14 mm/s at 1,000 W laser power, 1 kHz frequency, 6 bar assist gas pressure and 0.1 s piercing time. Drilling of sandstone used 14.33 KJ/mm^3 having a maximum rate of rotation of 57.46 mm/s at 1,000 W laser power and 2 bar. Lastly, drilling of shale used 8.13 KJ/mm^3 having a 45.05 rate of penetration that was achieved at 300 W, 5 kHz. Morphology report of drilled limestone has a melted region on its surface with small cracks due to powerful drilling intensity and reduced drilling time. High quartz in sandstone consumed more energy for melting and vaporising. This resulted in dehydration of clayey elements due to elevated temperature which improved permeability and micro-fracturing. Lastly, shale rock consumed the least energy as the sample did not have moisture content in it (Bharatish et al., 2019).

4.3 Intelligent drilling and charging

Automation in mining has enabled remote controlling of machinery which has proven to be more efficient, safer, and cheaper than using human personnel. The utilisation of automation has enabled unmanned operations of rock drilling jumbos, down-the-hole (DTH) drills, and underground charging vehicles. Drilling of rocks being the initial step of fragmentation in mining is a crucial step that affects the rate of production, operational cost, and safety in operations. A study by Li and Zhan (2018) reported the development of a rock-drilling jumbo that uses intelligent mining technology for efficient drilling operations whose intelligent flow diagram is as indicated in Figure 8. Working using hydraulics for drilling, the unmanned drilling equipment uses virtual reality for displaying the site conditions to the operator which include both audio and visuals to aid in remote controlling operations. Having its navigation guided by GPS, the drilling jumbo has autonomous movements which enable it to move from the dispatch area to the operation zone as well as identify the precise locations for drilling on the face (Li and Zhan, 2018).

Figure 8 Intelligent control flow chart for hydraulic drilling



Source: Li and Zhan (2018)

Based on the rock properties, the drilling jumbo adjusts its parameters for effective drilling which is supported by automated rock properties acquisition system, drilling rod, and a drill pipe bank. Furthermore, to reduce downtime, the automated drill rig is equipped with a blockage preventer (Li and Zhan, 2018).

However, there are places where rock-drilling jumbo cannot be effective in drilling such as in zones having ultra-high sections requiring deep hole drilling greater than 30 m and diameters of 100–150 mm. Such situations require DTH drilling which is mostly unsafe, difficult to operate, inflexible to achieve the required drilling design and leakage (Hwang and Jong, 2016). A study by Li and Zhan (2018) reported the development of automated DTH drill to support intelligent mining technology. The intelligent DTH system is equipped with autonomous driving and a hole location system, supported with GPS. Additionally, the DTH drilling machine was supported by an automated intelligent mining system that aids in drilling optimisation. This is achieved by analysing the impact of working parameters on drilling efficiency such as axial thrust, rotary speed, rotary torque, impact pressure, frequency, and drilling pressure. Furthermore, empirical formulae were developed for every selected drilling variable to determine variables affecting drilling efficiency. Therefore, that allows the selection of optimum drilling parameters such as air pressure, gas volume, and propulsion forces.

The blasting operation has the potential of being affected by numerous factors such as accuracy of drilling, depth of drill-hole and declination hole, anti-deviation technology was installed to prevent deviation of the drilling pipe in real-time to prevent errors (Hwang, 2015). Finally, the system is fitted with multiple drilling storage, automatic sorting, and anti-blocking resistance technology which allows automatic instalment of additional drill pipes based on the hole depth as well as prevent blockage, thereby improving efficiency.

Research by Wang et al. (2016) reported the utilisation of an intelligent charging system for blasting using an automated charging vehicle which is an integration of mechanical and electrical systems for transporting, mixing, and charging explosives and loading gun-hole. To improve efficiency, the charging system has automated pipe-reeling and pipe-feeding speed that allows digitalised feeding according to the blasting requirements. The intelligent feeding system is further embedded with safety systems that monitor and diagnose charging systems to identify any faults that may lead to secondary blasting (Wang et al., 2016).

4.4 Controlled blasting

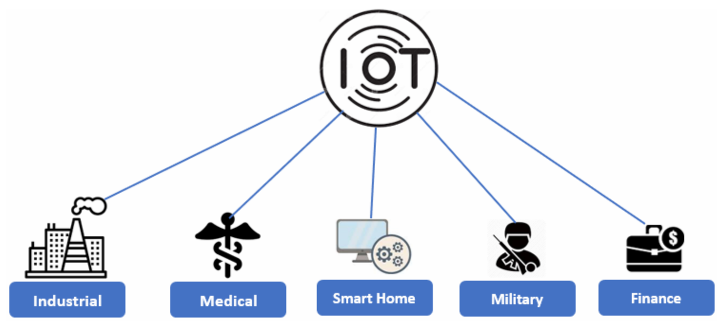
Blasting known as a destructive operation in mining, efforts have been made to reduce ground vibrations, flyrocks, air overpressures, over-breaks, and under breaks. The occurrence of such hazards does not only expose miners and surrounding communities to risks, but can also damage the environment leading to slope failure, rock subsidence, or even affecting the surrounding flora and fauna (Bhagat et al., 2020). To overcome such problems, careful blast designs must be established to ensure safe blasting takes place.

Air-decking has been used as a controlled contour blasting technique whereby columns are combined with air chambers using wooden spacers and gasbags used for production or pre-splitting blasting. The blasting techniques use superimposition of opposite directional detonation fronts in the air column before fragmentations of explosives to generate compression shocks whose direction relies on the form of charging, blasting equipment used, and initiation order (Lu and Hustrulid, 2003). Research by Pal (2021) reported that sub sequential increment of air gap volumes from 10 to 30% through reduction of stemming depth in a drill hole reduces the velocity of detonation. Examples of this include VARISTEM and Stem Lock Gasbag. VARISTEM technique improves blasting efficiency and reduces operation cost as it allows a unit blast design to cover a larger zone for blasting. Therefore, this saves on cost as fewer blasting materials are used for a larger area. On the other hand, the stem gas bag is a self-inflating borehole plug that blocks drill holes at any desired depth (Pal, 2021).

4.5 Internet of things (IoT) application

IoT is a specialty in computing which deals with the use of unique identifiers for data transfer between interrelated electronic devices over a network with little or no human interaction (Adebisi and Abdulsalam, 2021). Its application in various aspect of human endeavours include but not limited to Industrial, medical, home automation, military, business, etc. as illustrated in Figure 9 cannot be overemphasised when dealing with the complex nature of coal fragmentation. Similarly, Lawal and Kwon (2021) emphasised on the application of artificial intelligence in handling various problems in engineering. Recently, many industries including mining like its counterparts in agriculture, manufacturing, construction, oil and gas have subscribed complete automation.

Figure 9 IoT applications (see online version for colours)



IoT framework permits unfailing data transfer and visualisation remotely from various channels in diverse areas of engineering including different methods of mining. The operations guided by the use of other technologies including GPS, laser technology, intelligent drilling and charging gives room for a very high tendency of accurate data visualisation for decision making remotely. Harnessing information from desperate sources through IoT help to speedily report issues during coal mining operations far-off. This reduces production damage and escalates efficiency in coal mining. In literature, few mining operations are currently running on IoT assisted technologies due to some of its associated challenge and complications involved in underground operations. Attractively, administrative services and surface operations are gradually taking advantage of this technology in mines through remote monitoring of mining staff performance, transport equipment monitoring, office and workshop security to mention a few. However, running a smooth communication to remotely control coal mining equipment for data aggregation purpose and prompt decision making with the help of IoT still faces a real difficulty. Nonetheless, the possibility to join forces with existing technologies to develop imaginative way out in the enhancement of efficient fragmentation in coal mining is a possibility.

5 Drilling and blasting software

Numerous studies have enabled the development of drilling and blasting software to aid in the viewing of field images, modelling blast design, and optimising the fragmentation process. The development of such drilling and blasting software is as discussed below.

Developed in 2005, BlastMetriX 3D software allows 3-dimensional capturing of images at a range of 1.5 m which has improved data collection in mining and other earthworks using hand-held cameras. Additionally, the software automatically transmits data into 3GSM software for the generation of maps which are used for mine planning and designs. The creation of such maps has been instrumental in implementing effective blast designs as it aids in the production of actual bench geometry including bench face and surfaces. This aid in planning and optimising blasting operations as it provides the actual situation found in the site for blast design.

Additionally, further development created ShapeMetriX 3D that aids in digital characterising rock mass which includes geological maps especially in mining and geotechnical engineering. Furthermore, the generated 3D models show the exact orientation of drilled blast holes which can allow miners to adjust the design before blasting. Moreover, the developed models allow assessment of rock material using coloured zones which aid in evaluating blasting parameters such as burden and spacing. Further development of 3GSM has created Blast Metrix UAV which allows the creation of 3D imageries using drones to facilitate improved data collection of the entire mine which aids in face profiling and post-blast analysis.

Developed by the O-pit blast organisation, O-pit blast software aids in planning, controlling, and optimising drilling and blasting activities. The mode of operation of the software entails importing surface terrain data such as topography and geological information to enable blast planning for effective fragmentation. The software is also supported by the management section that enables miners to graphically display blast results, record blast information, and generate reports for every blast. Furthermore, the software analyses the blast designs to determine the effects of each parameter such as blasting patterns and explosives used. Moreover, the software has a tool for determining the fragmentation behaviour of various terrains which aids in the creation of confidence curves and predicting blasting effects such as fly rocks, ground vibrations, and noise which enables redesigning of the blasting systems. O-pit blast also supports data collection using drones for the generation of more accurate pictures of the bench geometries.

Developed by MineExcellence Company, Blades is a software that is dedicated to improving and optimising drilling and blasting and reducing safety risks. The software operates using input data which include coordinates of blast fields, diameters of drill holes, blast patterns, rock mass properties, face profiles, targeted fragmentation size, explosives used, and details of the surrounding environment to guide the miner about the charge distribution, initiation and delay time and distribution of fragmentation size. Furthermore, the software predicts the blasting effects such as flyrocks, airblasts, seismic vibrations, and fragmentation curves. To inject flexibility in operations, the software can be used both on computer systems as well as mobile phones. Additionally, the system accommodates data collection using drones for accurate data collection and post-blast analysis.

SHOTplus 5 premier was developed by Orica to support designing, analysis, and optimisation of blasting operations. To enhance performance, the software is embedded with timing tools for both pyrotechnic and electronic detonators together with options for various blasting designs to simulate various blasting scenarios, predict results and generate reports for blasting operations. Furthermore, the software allows 3D visualisation of the blasting design from various rotating and zoom tools that can enable the evaluation of critical blasting zones. Additionally, the software conducts performance analysis of selected blasting designs and shows the results of various drill hole orientations.

BlastmapTM III is a drilling and blasting software that was developed to optimise drilling and blasting variables in the shortest period possible by providing blasting designs to be adopted in the blasthole field including the number of explosives, location of drill holes, spacing, and burden. Developed by JKTech, JKSimBlast is a drilling and blasting software for simulating and managing blasting operations in mines for effective fragmentations. Despite the effort made by technology to improve mining operations, the coal mining industry has not yet fully adopted the advanced technologies which can potentially improve recovery, reduce manual work, decrease cycle times and improve safety.

6 Methods of future drilling and blasting operations due to technological innovations

Despite the effort in adopting new technologies in mining, the industry continues to research how best to improve production, enforce safety, and reduce environmental pollution and hazards to make the sector sustainable.

To allow the mining industry to have seamless production, it is important that drilling and blasting operations are instrumented, interconnected, and intelligent from exploitation to processing in a single digital system. Such systems will allow real-time monitoring and virtual simulations of operations to optimise production and reduce unwanted losses. Fully automated drilling and charging operations will allow zero-entry of mining personnel, thereby aiding in eliminating fatalities from drilling or blasting incidences. Furthermore, reduction of operation costs may allow mining companies to tap reserves that could not previously be mined due to low grades.

Leveraging the IOT, mining companies will be able to collect real-time data using complex sensors installed in strategic locations in the mines. This will be beneficial in helping miners make smart and informed decisions to increase efficiency, safety and reduce the cost of operations. For example, using IoT, miners can improve haulage efficiency by evaluating optimum loading time and subsequently, reducing idling time. Furthermore, the usage of cloud computing will enable miners to interact in real-time to improve synergy in operation and work towards improving productivity and safety.

To ensure that mining companies comply with various policies and act responsibly in their blasting, blockchain technology will help mining companies to generate and maintain transaction records that can allow responsible parties to physically track mined minerals from mining to processing to exportation. Furthermore, the technology can allow the identification and trading of ore bodies while still in an in situ state. In addition to that, artificial intelligence can help miners use prediction modelling which can help in decision making including production and hazard management. To inject environmental sustainability, the mining industry will shift towards electrification of drilling machinery to reduce carbon emissions. Furthermore, the adoption of such technology will help mining companies cut down operation costs for ventilation used in cooling such machinery.

7 Summary and concluding remarks

7.1 Summary

Drilling and blasting operations are crucial in ensuring that ores are broken into the required sizes for easier material handling. In coal mining, drilling and blasting is critical in stripping of overburden for access to coal seams and increasing of permeability for gas extraction or reducing rock pressure to avoid gas burst. In overburden stripping, studies have reported the cases of coal seam damage due to excess usage of explosives or expensive stripping operations due to inefficient blasting operations which require additional material handling to aid in stripping of waste. To deliver effective overburden extraction operations, it is essential to understand the properties of the material including depth, hardness, lithology and presence of geological features. Thereafter, simulation can be done using blasting software to determine the most optimum drilling design.

To drill holes with high accuracy, there is a need of leveraging on modern technology as practiced in other mining operations such as usage of GPS drilling rigs that will help in avoiding overdrilling of holes and ultimately help in damaging of coal seams. To save excessive usage of energy in drilling of the overburden, mine companies should adopt laser drilling technology which will not only save drilling cost but also, shorten the cycle time. Furthermore, artificial intelligence should be adopted to predict the behaviour of rocks overlying coal seams, which will largely help mining companies save on exploration drilling. After drilling, right charging techniques should be used to deliver the right amount of explosive energy required to fragment the waste without damaging the coal seams. To ensure that detonation energy is well utilised to blast the rock, there is a need of utilising suitable stemming material such as the environmental friendly polyethlyne plug.

7.2 Concluding remarks

Technological innovation in drilling and blasting is a crucial aspect in the mining industry as it helps in improving the efficiency of operations, reduces the cost of operations, ensures safety as well as meets societal and environmental needs. Several technological trends are the main factors shaping rock fragmentation which include integration of GPS, drilling using laser technology, intelligent drilling, and charging, controlled blasting, and usage of software for blasting optimisation. Integration of such advancement has proven to improve productivity and reduce safety risks. Furthermore, rock fragmentation industry has the potential to improve efficiency using IoT, robotics, sensors, blockchain, and automation.

However, despite the focus on the mining industry on inventing advanced technological drilling and blasting methods, the level of adoption of such methods is low in coal mining industry. This is due to existing gaps that can be improved through intensive research and development in the industry and research institutions to fast-track the best way to implement such new technologies. Furthermore, there is a need to adequately train miners on the newly introduced technologies so that they can familiarise themselves and effectively deliver their roles. For the coal mines to improve on recovery, decrease operation time and enhance safety, this study recommends the following:

1 Integration of artificial intelligence and ML in exploration to allow prediction of rock properties that will help in understanding the geological formation of overlying rocks above coal seams. A clear comprehension of overburden will aid in delivering effective blasting design to avoid damaging of coal seams.

2 Utilisation of drilling and blasting software such as Blastmap TM III, SHOTplus, Blades, O-pit blast and ShapeMatrix that can deliver optimum blasting fragmentation based on geological conditions. This will not only help in improving recovery but also promote safety by avoiding excessing ground vibrations and flyrocks.

3 Integration of GPS in the jumbo drill rigs to harness maximum benefits from drilling operation. Such technology will deliver accurate drillholes which will reduce damaging of coal seams.

4 Adopt mechanised charging that will ensure the right amount of explosives are used per drillhole in the right location.

5 Utilise suitable stemming material to confine detonation energy for rock fragmentation.

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