Excavation Technology for Hard Rock - Problems and Prospects

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Abstract

Civil engineering projects have greatly benefited from the mechanical excavation of hard rock technology. Mining industry, on the other hand, is still searching for major breakthroughs to mechanize and then automate the winning of ore and drivage of access tunnels in its metalliferrous sector. The aim of this study is to extend the scope of drag bits for roadheaders in hard rock cutting. Various factors that can impose limitations on the potential applications of drag bits in hard rock mining are investigated and discussed along with alternative technology options.

Key words: Hard Rock Excavation, Roadheader, Drag Bits, Synthetic Bit, Tool Wear, Water Jet Assistance.

1. Introduction

Mechanical excavation has proved to be extremely effective in coal measures and evaporitic rocks. Excavation technology for hard rock cutting holds substantial prospects for selective mining, continuity and automation of operations over drill-blast-muck out system that suffers from cyclic nature of its operations. Presently available continuous rock cutting technology is, however, restricted generally to the excavation of relatively `weak rocks` due to its capital and running costs and the physical size problems associated with mechanical design [1].

Tunnel Boring Machines (TBMs), roadheaders and other rock cutting machines available for rock cutting mainly use two types of cutting tools, namely, indenters and drag picks. Indenters generally associated with full face cutting operation of TBMs and capable of cutting hard rock with uniaxial compressive strength (UCS) of up to 350 MPa, are mainly confined to civil tunneling projects. Roadheaders with their drag bits, on the other hand, are favored for mining operations for their flexibility and maneuverability and can successfully excavate rocks with a uniaxial compressive strength of 80 MPa while heavy duty roadheaders can cut rocks up to 100 MPa.

The fundamental constraint on the ability to cut harder rocks in excess of UCS of approximately 100 MPa derives from the limited strength of the rocks i.e. having strength greater than 100 MPa, more power has to be transmitted through the cutting tools to fracture the rock. But, however with the existing hard rock excavation technology, increasing machine power alone will not enhance the tool life. Further, under such harsh cutting conditions, the amount of heat generated adversely affects the tool material properties which compound the tool life problem. Water jet assistance is claimed to ameliorate these factors and a better tool life is obtained. In overall configuration of the design of a hard rock cutting machine, the tool has thus assumed the pivotal position.

Increased machine power and rigidity needed for hard rock excavation are other limiting factors, but it is the pick-end performance of the tool material which is proving to be a major stumbling block. Researchers, meanwhile, continue to explore for breakthroughs [2].

The Department of Mining and Mineral Engineering at the University of Leeds, U. K., initiated a research programme jointly with HRDK, a Canadian organization for mining research, on roadheaders with the aims to obtain quantitative understanding of the different factors such as cutting force components experienced by a drag tool when excavating nickel ore and other associated mine rocks such as granite and felsic gneiss – very abrasive rocks ranging in UCS from 33 MPa to 350 MPa - the wear on the cutting tools and what factors brought about tool failure.

A secondary objective was to investigate the factors which hold potential to extend the above mentioned limits with water jet assisted cutting; using different tool materials and geometries; determining the effects of cutting speed and water jet position with the goal of achieving optimum operating conditions.

2. Principal Rock Cutting Variables

A number of drag pick cutting theories of rock have been presented to describe the mechanism in simplified terms and mathematical expressions with the purpose of gaining a better understanding of the cutting process and to improve the design of the picks and the machine. Various aspects of rock cutting with picks have been reported from researchers. Due to wide range of cutting conditions, there are some conflicting views but some generalities do emerge which can be regarded as fundamental features of pick cutting:-

1. Both cutting force and normal force increase with depth of cut for all the picks. In most circumstances the increase is more or less linear [3, 4, 5, 6].

2. Specific energy reportedly decreases with increasing depth of cut, rapidly at first then more slowly, [3, 7, 8] attaining some minimal value, after which cutting efficiency decreases with increased depth.

3. Cutting and normal forces decrease non-linearly with increasing rake angle. The optimal rake angle is deemed to be 20^{o} beyond which pick strength and its survival is at stake [3, 9,10, 11].

4. Cutting and normal forces have been found to increase approximately linearly with the rock unconfined compressive strength, correlation with tensile strength may be more appropriate for laboratory conditions since rock fails in tension [9, 11].

5. For a chisel shaped pick, cutting and normal force increase with pick width [3, 4].

6. The pick forces for a new tool reduce with increasing back clearance angle by 30^{o} as reported by Kenny and Johnson, while Mellor states a decrease of up to $+5^{o}$ only [4, 9].

7. Cutting speeds have no discernable affect on pick cutting force or specific energy when wear is not a factor [12].

8. Cutting with an array of picks involves each pick passing through the rock in sequence. Each pick thereby has the opportunity to exploit the relief provided by an adjacent groove produced by a preceding pick in the sequence. The value for the optimum ratio for spacing groove and depth of cut for pointed picks has been found to vary from 1.5 to 3.0 according to rock type [8, 3].

3. Factors Effecting Tool Life

Presently, tungsten carbide is the most widely used material for rock cutting tools because of its relatively high hardness and high toughness properties. The total useable life of a cutting pick for any excavation machine is dependent upon its wear and fracture resistance, which in turn will depend on parameters such as pick geometry, operational factors, the properties of the pick material and the properties of the rock being excavated. Currently, understanding of these parameters is not well correlated and prediction of bit life is still a trial and error process. One would, however, benefit from an understanding of the interrelationship of pick wear and the efficiency of the cutting system.

3.1. Pick Geometry and Operational Factors on Wear

Mainly two types of picks are in use; `radial` and `conical; both vary in their angle of attack, geometrical shapes, the manner these are attached to the machine and rotational movement during cutting operation. A third type, Forward-attack bit, attempts to incorporate positive features of both for improved operational efficiency.

Studies conducted on the geometrical configuration and operational factors on tool wear report as under:

1. Most wear resistant tools have a large negative rake angle and rounded cutting edges [13].

2. Fowell has also reported improved wear resistance for round edged tools [14].

3. The ideal cutting tools should be chisel shaped with a large rake angle and a back clearance of between 5^{o} and 10^{o} [15].

4. Bits should be selected for their wear and fracture resistance and the tool tip shape is not likely to be a significant factor when measured over the whole tool life [5].

5. Radial tips are more quickly affected by wear than conical tools [16].

6. Conical tools are more susceptible to frictional sparking [5].

7. Tool forces and specific energies increase in relation to increasing wear flats [4, 11].

8. Tool forces increase continuously with depth and spacing, and the angle of attack for point attack tools has an important effect on cutting efficiency [7].

9. Increase of cutting speed especially when a critical level is surpassed, causes increased wear [4, 17].

3.2 Effect of Rock Properties on Wear

Sedimentary rocks have almost exclusively been the main rock types where drag tools have shown fair degree of success. The important properties of sedimentary rocks that influence tool life are identified with hard mineral content, (commonly quartz but not always so), grain size and angularity and cementing materials [18]. Limited use of drag tools has been reported in igneous and metamorphic rocks due to their inherent strength and tool degradation properties.

The most commonly measured rock property that influences the tool wear is the abrasivity. A proportional relationship between quartz content and abrasiveness has been noted by West [19]. In hard rock, frontal wear causes flaking and chipping of the carbide. Larger wear spalls were produced when drilling in granite. While drilling sandstone and granite abrasive wear is more marked for the quartz-rich sandstone than in the harder, less abrasive granite; it is postulated that impact fatigue increases if the impact energy is increased for higher penetration rates [20].

Cutting tool materials and their properties have a direct bearing on the tool wear and its useful life. Selection of suitable tool material for the given operating conditions needs due consideration.

4. Tungsten Carbide as a Cutting Tool Material

Tungsten carbide is the most common cutting tool material used in rock cutting. The factors that influence the performance and life of tungsten carbide are strongly dependent on the raw materials and the manufacturing techniques. Fowell [14] and Altinoluk [11] cover these aspects in their works. The composition and micro structure of the constituents of tungsten carbide ultimately determine its physical and mechanical properties.

Cobalt and carbon are the most important compositional variables in producing tungsten carbide with a suitable blend of hardness, compressive strength and transverse rupture strength. Cobalt ranges from 6 to 15 % by weight whereas theoretical content of pure tungsten mono carbide is 6.12%. Any excess or deficiency of carbon within 6.0 ± 0.11 limits has significant effect on hardness and strength [11, 14, 21].

In general, any alloying impurities like iron chromite, nickel, sodium or sulphur can result in poor combination of hardness and strength. Small additions of titanium carbide (3 – 5% by weight), however, could prevent grain coarsening and increase hardness without affecting the transverse rupture strength [22]. Equally important is the grain size control; hardness and compressive strength increasing with decreasing grain size, whereas the desirable grain size for best rupture strength is from 1μm to 3 μm [22, 23].

Porosity in the alloys' structure is an unwanted parameter. High porosity gives rise to poor transverse rupture strength but in hard metals, high densities up to 99.5% are achieved and uniformly distributed porosity is usually present, which is not so harmful [24].

4.1 Gross Failure of Tungsten Carbide tools

Tungsten carbide is a brittle material and is stronger when loaded in compression than in tension. Further, its strength is enhanced in triaxial loading. Consequently bit designers aim to ensure that the bit geometry and the mode of loading will not cause tensile stresses to be applied to the bit during cutting. Also, where possible, they would mount cemented tungsten carbide inserts in a tool body in a manner such that triaxial compressive stresses are applied to the inserts. Despite these precautions, the bit inserts fail in a brittle manner, particularly in hard rocks. One of the main factors responsible for this type of failure is the impact loading of the bits; impact blow induces compressive stress waves in the bit insert, which are partially reflected back from the available free surfaces as tensile stress waves, thus causing failure. In other cases, fatigue can cause an incrementally extended crack with each loading cycle until it fails. To prevent or minimize this type of cyclic failure it is important to minimize vibration and a stiff drive to the cutting head is required.

The failure may occur due to poor carbide with low toughness and tensile strength, pores in the carbide or a thick braze. A thin braze allows the waves to be transmitted to the insert carrier where it will be attenuated without damage [25]. Higher cobalt content also prevents impact failure but due to lower hardness it will suffer more damage because of abrasive wear.

4.2. Temperatures during Cutting Operations and Tungsten Carbide Tools

The mechanical, chemical and metallurgical properties of tool materials are often temperature dependent and any abnormal rise in temperature during cutting operations directly affects tool properties like hardness and strength. Tool speeds underground are generally in excess of 1m/sec and in continuous operation, tool tips would reach very high temperatures, ranging from 600^{o} C to 900^{o} C [4]. Tungsten carbide tools at such high temperatures begin to soften, thus causing unwanted wear and early failure of bits.

5. Polycrystalline Diamond Compact (PDC) Cutting Tools

Hard rock cutting technology has been searching for synthetic cutting tool materials that can withstand the rigorous operating conditions and still can cut faster and longer. This kind of durability from tools sets increasing demands for higher abrasive wear resistance and toughness. As far as abrasive wear is concerned polycrystalline diamond compact (PDC) tools are now available with 5-6 times higher hardness than tungsten carbide. However, PDC is more susceptible to brittle failure than cemented tungsten carbide, because its fracture toughness is 6.3 ksi as compared to 10.8 ksi of tungsten carbide with 6% cobalt [26]. Traditional abrasive wear is possible for synthetic diamonds when employed in coring bits. However, these diamonds are prone to severe thermal degradation at temperatures above 750^{o} C [27]. Synthetic diamond tipped drag tools hold a lot of promise as the next generation of hard rock cutting tools. Further research needs to be done to provide answers to all the problems of extreme rock cutting conditions.

6. Water Jet Assisted Rock Cutting

The use of water jet assistance with drag picks represents a technology which can overcome some of the limits of conventional rock cutting. Many of the potential advantages include: reduction of cutting forces, reduction in tool wear, temperature control during cutting so eliminating sparks, reduced dust hazard and overall improved cutting process.

Mechanically assisted water Jet cutting has successfully been employed in coal strata and other similar formations, but use of this mode of cutting in hard rock is minimal. It is the application of water jet assisted cutting which holds promising prospects for increasing the overall efficiency of cutting operations, including life of the cutting tools.

7. Research Programme

There are areas such as; suitable tool materials, tool design, water jet assistance in hard rock cutting and similar other factors requiring further studies for optimizing available technology and for more innovative alternatives. Many of these were investigated during a study conducted at the Department of Mining and Mineral Engineering, University of Leeds, U. K. [28].

7.1 Objectives

The main objectives of the programme were:

1. Testing of selective cemented carbide grades and geometries to establish guide lines for optimum cutting tool parameters for hard rock cutting.
2. Establishing the potential of medium-high pressure water jet assistance in the hard rock cutting process and its mitigating effects on cutting forces and tool wear.
3. Examining the effect of cutting speed on cutting forces and tool wear.
4. Investigating the effect of water jet positioning.
5. Examining the methodologies and practicability for temperature monitoring in the cutting process and its effect on tool wear and cutting forces.
6. Evaluating the performance of PDC tools in hard rock cutting.

7.2 Experimental Set Up

The department was provided with hard rock samples for determining their physical properties and standard cuttability tests. The samples comprised of felsic gneiss; mixed ore and granite block 1 (with wide bands of granite in the ore); mixed ore and granite block 2 (with relatively thinner bands of granite) and a homogenous ore block; approximately one cubic meter in size for full scale testing with a selected range of tungsten carbide tools especially developed for hard rock. Some of the results are shown in Table 1 and Table 2 to give an appreciation of the rocks involved in the project.

The samples supplied by HDRK exhibited cutting characteristics which indicated difficult cutting prospects for a drag tool equipped tunneling machine. Further testing by HDRK on their testing machine, TM60, however, indicated that the sulphide nickel ore and some peridotites could be in the range of this machine. An assessment was made that a certain amount of hard waste rock in and around these sulphide ore bodies could be tolerated, though gneiss, quartzite and norite rocks were generally outside the range of present technology in terms of tool consumption and rate of extraction. This project was started as a challenge for full scale testing of tools and available technology in hard rocks, using the basic criteria described above.

An extensively modified 50 tonne linear planer rig [29] (Figure 1.) was used to perform these standard cuttability tests, as this apparatus afforded the rigidity necessary to achieve a 5 mm constant depth of cut. The other standard parameters of the tests were: a cutting speed of 0.15 m/s; an unrelieved cutting mode; a 12 mm wide chisel (tungsten carbide) tool with -5^{o} rake angle and a 5^{o} clearance angle. All the cuttability tests were carried out on this machine under conditions of speed, line spacing, water jet pressure and other cutting parameters simulating those on the HDRK TM60 roadheader being tested by the sponsors for one of their nickel ore projects in Canada.

The planer rig was used for cutting tests after necessary instrumentation. A block of selected rock was mounted in concrete on the rock planer. The design of the rock planer is such that the rock sample can be traversed from side to side beneath the cutting tool to alter the spacing between successive cuts. The depth of the cut is fixed by lowering the cutting tool with respect to the surface of the rock with vertical screw jacks that support the entire cutting mechanism. Hydraulic clamps held the rock planer rigidly during testing. A hydraulic cylinder forces the cutting tool through the rock at the selected speed.

Force measurement was accomplished by means of a strain gauge 150 kN triaxial force dynamometer.

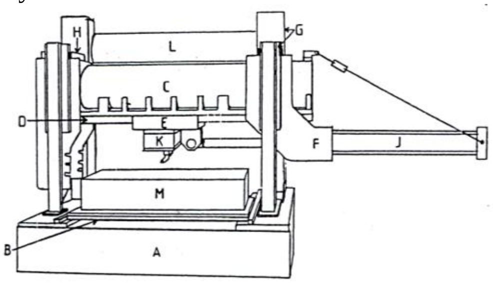
Table 1: Some physical properties of rocks used for Standard Cuttability Tests

Rock	Compressive Strength (MPa)	Tensile Strength (MPa)	Density (g/cc)	Cerchar No. CAI (0.1 mm)
Peridotite	160.7	16.0	3.05	2.97
Felsic Gneiss	303.0	28.8	2.67	6.26
Granite	220.0	20.0	2.72	4.70

Table 2: Standard Cuttability Tests of rocks

Rocks	Mean Peak Cutting Force (kN)	Mean Cutting Force (kN)	Mean Peak Normal Force (kN)	Mean Normal Force (kN)	Specific Energy MJ/m^{3}	Wear Flat mm/m
Peridotite	16.22	5.25	11.91	7.46	64.0	0.41
Felsic Gneiss	31.10	11.6	25.2	14.0	150.0	0.97
Granite	31.90	15.2	43.4	28.1	162.8	1.13

The dynamometer is calibrated in three perpendicular directions: parallel to the cutting direction (cutting force); perpendicular (normal or thrust force); and transverse to the direction of cutting (sideways force). The signals from the dynamometer were recorded on an FM tape recorder and subsequently transferred to a PC for analysis.



A. Structure base
B. Specimen table
C. Slide assembly strengthening beam
D. Slide bed
E. Cutter slider
F. Hydraulic cylinder support frame
G. Slide assembly guides
H. Vertical stiffeners (clamps)
J. Hydraulic cylinder
K. Dynamometer and cutting tool
L. Main structure strengthening beam
M. Rock specimen

Figure 1. The 50 Tonne Rock Planer used during present study [29].

High pressure water jet assistance was supplied by an intensifier type water pump. A calibrated diaphragm type transducer was used to set the water jet pressure. Tungsten carbide water jet nozzles with a 30^{o} contraction angle were used throughout the experiment. The initial nozzle diameter was of the order of that found to be a practical in the field, namely around 0.6 mm. A nozzle of this size results in a lower jet pressure than could be obtained at a smaller diameter, but the requirement of preventing excessive nozzle blockage was seen to be a critical field factor. Water pressure alone did not reduce the force components but the quantity of water (nozzle size) and the placement position of the nozzle were also important factors.

All the PDC tools used in this research were of conical point attack design. Several tool design compromises were made between the established factors that result in efficient cutting and the need to maintain a tool with an effective cutting life. Hurt and Laidlaw [5] have pointed out that with hard rocks, the effect of tool geometry diminishes rapidly as the tool wears and what assumes overriding importance is the fact that the tool does not suffer gross failure but continues cutting and offers a reasonable working life. This relates to the observation that the PDC lasted longer if distributed over the entire surface of the tungsten carbide substrate and the tool had no sharp edges. A certain rounding of the tip was considered important to maintain tool life.

7.3. Variables Tested

Commercially available tools of different compositions and makes were used for testing variables that affect the operating efficiency of the hard rock excavation. Cemented carbide tools, cutting speeds for different tools, water jet positions during cutting, cutting tool temperatures and testing of PDC tools are some of the variables investigated to make an assessment of better alternatives in trying to achieve the objectives of this study. Listed below are Tables 3 – 8 giving information on the variables tested, along with general operating factors under which these test were undertaken.

Table 3.Testing of Cemented Carbide Tools

Variable	Description
1. Radial Tools	
a) Carbides grades	4 coarse grained carbide tools (5-7μm) with 8-14% cobalt content by weight; two medium grained tools (3 - 5μm) with 10-14% cobalt content by weight.
b) Geometry	2 geometrical shapes with attack angle of 90^{o} and clearance angle of 10^{o}.
2. Conical Tools	
a) Carbide grades	4 tools with cobalt content from 10.5 to 15% by weight.
b) Geometry	2 point attack, low energy; cone angles 70^{o} and 98^{o}. Angle of attack 52^{o} and angle of clearance 5^{o} and 7^{o}.
3. rock	Nickle ore block, felsic gneiss, mixed ore and granite block 1.
4. Water jet assistance	Without jet (Dry), cutting with 28MPa jet pressure.

Table 4. Cutting speed Trials

Variable	Description
1. Tools	Radial (two), conical (one) pencil point.
2. Cutting Speed	0.3 m/s, 0.6 m/s and 1.0 m/s.
3. Water jet	Without jet (dry), cutting with 28 MPa jet pressure.
4. Rock	Mixed ore and granite block 1.

Table 5.Water Jet Position Trials

Variable	Description
1. Tools	Conical (one), radial (two)
2. Water Jet Position	External jet in front of tip
a) Conical Tools	Through tip centre Through tool, front jet Through tool, back jet
b) Forward Attack	Through tool, front jet Through tool, back jet
3. Rock	Mixed ore and granite block 2

Table 6.Temperature Measurement

Variable	Description
1. Tool Type	Radial (two)
2. Method of Temp Measurement	Thermocouple inside tool, Infra-red gun for tool tip.
3. Thermo Couple Position in Tools	10 mm, 5 mm, 3 mm from tool tip.
4. Water Jet Assistance	Without water jet (dry) cutting with jet at 28 MPa pressure.
5. Rock	Mixed ore and granite block 2.

Table 7. Testing of Polycrystalline Diamond Tools

Variable	Description
1. Tools (Megadiamond)	Radial, conical
2. Geometry	
a) Radial	U – bottom, V – bottom
b) Conical	Six different geometries
3. Rock	
a) For Radial	Felsic gneiss
b) For Conical	Felsic gneiss, mixed ore and granite block 1

While details of these tests are given else where [28], all the linear test work was done under conditions similar to those on the TM60 machine with regard to operational factors such as speed and spacing of cuts. For temperature measurements, a series of continuous and intermittent cuts were carried out which closely mirror a tool on the machine over a period of cutting time. The general operational factors are given in Table 8.

Table 8.General Operating Conditions.

Variable	Description
1. Depth of Cut	10 mm
2. Spacing between Cuts	25 mm
3. Cutting Speed	0.6 m/s
4. Skew Angle for Conical Tool	8^o off set
5. Cutting Mode	Relieved on one side
6. Water Jet Assistance	
a) Jet Fluid	Water without additive
b) Stand off Distance	85 mm
c) Lead Distance	1 mm to 2 mm
d) Jet Position	In front of tip
e) Jet Pressure	28 MPa
f) Nozzle Dia. For External Jet	0.43 mm
g) Nozzle Material	Tungsten carbide
h) Angle of Jet with tip of Tool	10^o

7.4 Discussion of Tests Results

The nature of the experiments in this project and the heterogeneity of the rocks both demanded as many replications as possible. In particular, the testing and performance of the tools certainly needed a cutting distance long enough to have an idea of overall efficiency throughout their life. Also, a wider range of data from a number of replications is important to minimize the experimental and standard errors. Unfortunately, cutting in these small quantities of hard rocks placed limitations on the cutting equipment, and restricted the cutting distance and repetitions possible.

The four post steel dynamometer which was available for this project was only capable of measuring cutting forces up to 100 kN. The initial studies on the rocks under consideration showed that only 4 meters of cutting with tungsten carbide tools would be needed to generate forces above that limit. It was, therefore, decided that 3 meters of cutting would be carried out with each tool under different cutting conditions.

Because of the large number of variables involved in cutting with drag bits, it was not possible to include all variables in this study. Selected variables have thus been tested at different levels depending upon the importance of each. Hence any conclusions drawn in these investigations are applicable only to the conditions in the laboratory as observed.

7.4.1 Testing of Cemented Carbide Grades

Six different cemented carbide grades for radial tools and four for conical tools were tested in ore, mixed ore and granite block 1 and felsic gneiss. The tungsten carbide tools tested were able to cut the ore and also a certain amount of waste granite under the given cutting conditions; none of the tools tested showed gross failure by fracture during ore and mixed ore and granite block 1 trials. The best cemented carbide for radial tools was the one with 10% cobalt content by weight, as it exhibited optimum hardness and toughness for radial tool application in these rocks.

Further, for conical tools, the best carbide grade was found to have an average cobalt content of 10.5% which is quite close to the best carbide grade for radial tools. The conical tools were not rotated during the cutting tests and their rate of increase in normal force generally was more than for the radial tools. Both these tools were tested in felsic gneiss under the same cutting conditions but gross failure of the conical tools and extreme wear of the radial tools showed that felsic gneiss is not cuttable by these tools at the present level of technology available.

7.4.2 Water Jet Assistance

Water jet assistance during cutting operations helped in the reduction of cutting forces by 20% to 50% and lowered the temperatures by up to 50%. As a result lower wear flat was observed, being approximately half compared to dry cutting.

A number of jets and filter arrangements were tested for jet quality and flow rate. The filter element was found to cause the jet to lose coherence, especially the brass pad filter but the mesh wire type filter was found to produce good coherence.

Various positions of water jet were tested. The jet behind, through-tool showed the greatest benefit but at the expense of a much higher flow rate and proved to be a weaker tool because of the introduction of a hole in the nozzle. Also the stand-off distance was only 4 mm away from the apex tip. In hard rock cutting, water flow rate is important for cooling purposes but some satisfactory heat reducing arrangement is needed at the cutting point, which at the same time should avoid other problems caused due to the excessive use of water.

7.4.3 Effect of cutting Speed

As given in Table 4, various types of cutting tools with varying composition and makes were tested, with and without water jet assistance, at different cutting speeds. While details of the tests conducted and the ensuing discussions are given elsewhere [28], it was interesting to note that the wear flat on the tool and rate of increase in cutting force component showed dramatic increases from 0.3 m/s to 1 m/s cutting speed. The difference between 0.6 m/s to 1 m/s was negligible after 3 meters of cutting in terms of the tool and rate of normal force increase but at 0.3 m/s much lower wear and lower forces were observed.

Water jet assistance is essential to reduce the wear rate at low cutting speeds but for higher speeds the benefit was lost for the conditions employed during these investigations. There is benefit in cutting speed reduction in prolonging tool life but the production rate may not be acceptable. Such a situation may be justified in terms of tool costs when excavating isolated pockets of hard rock.

7.4.4 Temperature during Rock Cutting

The temperatures measured and estimated in this study showed that these approached the level at which tungsten carbide alloys begin to soften and the hardness and strength may be affected badly.

In dry cutting conditions, the forces, wear flat and temperature of the tool were higher than in water jet assisted cutting, confirming that water jet assistance is important for hard rock cutting.

A relationship was observed between the normal force component, the wear flat and temperature during cutting. This showed that the temperature rose with a rise in normal force and the temperature was found to fall when the normal force reduced due to reduction in the depth of cut.

7.4.5 PDC Tools for Hard Rock cutting

During cutting mixed ore and granite, and felsic gneiss no abrasive wear was observed on the PDC tools, which demonstrates their virtue of considerable abrasive wear resistance. At higher depths of cut or in stronger rock, the normal force increases, thus inducing gross fracturing in the PDC tools because of their low toughness property.

Further, the experiments with these PDC tools exhibited that cutting forces for sharp geometries were lower than for circular shaped bits, but sharp geometries are more prone to gross failure.

8. Conclusions

While mechanical excavation has achieved a fair degree of success in relatively `soft` rocks (coal and evaporates), the availability of this technology continues to struggle in the hard rock regime. TBMs with their roller cutters have performed well in hard rocks for mostly civil engineering projects. Flexibility and selectivity needed for mining similar rocks can be provided by roadheaders but the limitations posed by the use of such machines need resolution before their benefits can be fully utilized. The research programme as detailed in the preceding pages is an attempt to find answers for some of the problems faced during hard rock mining with roadheaders.

Most importantly, the cutting tools represent the major bottleneck in the application of mechanical excavation to hard rock by roadheaders. Selection of proper tungsten carbide grades can certainly provide relief in optimizing the excavation operation. With increased rock strength, an equally powerful machine is needed to match the power requirement. This arrangement, however, places unreasonable burden on the tool. The use of water jets can ease the burden on drag bits during high temperature cutting operation by lowering the heat generated at the tip end of the tool and thus enhancing the tool life. A new material like polycrystalline diamond compact (PDC) for drag bits is substantially better than tungsten carbide because of its higher abrasive wear resistance but suffers gross failure because of its low toughness. Efforts [2] are underway to develop a new generation of synthetic diamond tipped tools with necessary toughness and increased wear resistance to excavate rocks with unconfined compressive strength of 200 MPa and above.

Further work is needed to find solutions to the problems faced in the mechanical excavation of hard rocks. Development of synthetic tools has already been reported. Study of the relationship between wear mechanism and carbide composition, evaluation of the performance of various geometries of the cutting tool, testing of rock cutting at higher speeds and with various water jet pressures and flow rates and percussive action in addition to drag bit linear cutting are some of the areas which could be looked into to help improve the overall efficiency of mechanical cutting operations of hard rock.

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