

Cutting strong rock with a drag bit assisted by high-pressure water jets

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SYNOPSIS

Experiments are described that led to the discovery that coherent high-pressure water jets directed immediately ahead of drag bits while they are cutting strong rock reduce the magnitudes of the forces on the bits significantly.

Tests were carried out to assess the effects of the pressure of the water jets on bit-cutting performance. The pressure was varied between 10 MPa and 50 MPa, the water flow rate being a constant 30 l/min. Over this pressure range, the force on the bit was reduced to the extent that the depth of cut of the bit was at least doubled with the point of impingement of the jets optimized. Forces on the bit were found to be particularly sensitive to the point of impingement of the water jets relative to the bit. The optimum configuration was found to be with two jets, one directed towards each corner of the bit and impinging on the rock approximately 2 mm ahead of the leading edge of the bit.

Experiments in which a drag bit and high-pressure water jets were used to cut strong abrasive quartzite in the underground mining situation have demonstrated a potential increase of up to five times in the average depth of cut due to reduction of the forces on the bit. The results from the underground tests indicate that the life of the bit is improved significantly — by a factor of approximately two — when high-pressure water jets are used.

SAMEVATTING

Eksperimente word beskryf wat gelei het tot die ontdekking dat samehangende hoëdrukwaterstrale wat onmiddellik voor sleepbore gerig word terwyl hulle sterk klip sny, die grootte van die kragte op bore aansienlik verminder.

Daar is toetse uitgevoer om die uitwerking van die druk van die waterstrale op die boor se snyprestasie te bepaal. Die druk is tussen 10 MPa en 50 MPa gewissel terwyl die watervloei konstant op 30 l/min gebly het. Oor hierdie drukbestek is die krag op die boor in so 'n mate verminder dat die snydiepte van die boor minstens verdubbel is met die trefpunt van die strale geoptimaliseer. Daar is gevind dat die kragte op die boor besonder gevoelig is vir die trefpunt van die waterstrale met betrekking tot die boor. Daar is gevind dat die optimale konfigurasie met twee strale is waarvan een na elke hoek van die boor gerig is en die rots ongeveer 2 mm voor die voorraad van die boor tref.

Eksperimente waarin 'n sleepboor en hoëdrukwaterstrale gebruik is om sterk afskurende kwartsiet in die ondergrondse mynboutoestand te sny, het 'n potensiele toename van tot vyf maal die gemiddelde snydiepte getoon as gevolg van die vermindering van die kragte op die boor. Die resultate van die ondergrondse toetse dui daarop dat die lewensduur van die boor aanwerklik verbeter word — met 'n faktor van ongeveer twee — wanneer hoëdrukwaterstrale gebruik word.

Introduction

The efficiency of a rock-breaking process is a function of the size of the rock particles produced¹, so that an efficient method of rock cutting, comprises cutting a slot and then breaking a larger volume of rock into the slot. Drag bits, which are the most efficient tool for cutting brittle materials² and are widely used for cutting low-to medium-strength rocks, are not commonly used to cut in hard strata, since the lower bit life is generally unacceptable.

A system using drag bits to cut slots in strong, abrasive quartzite has been adopted by the Chamber of Mines Mining Technology Laboratory with the aim of developing a method of selective mining in the narrow gold-bearing reefs of the Witwatersrand System³. The technique used is to cut a slot in close proximity to the gold reef and then to break out the reef with impact-driven wedges. Pilot production trials were commenced at Doornfontein Gold Mine to establish the feasibility of using drag-bit rockcutting machines for stoping at a steady rate over a long period of time⁴.

During the course of the investigation to improve the life of the bit, it was discovered that high-pressure water jets directed at the bit strongly influence the magnitudes of the forces on the bit. The majority of the bits used

during the early stage of these trials failed at the braze joint between the tungsten carbide insert and the steel bit body. Laboratory experiments using thermocouples to measure the temperature at the bit braze joint during the cutting operation indicated that very high temperatures were causing thermal deterioration of this joint. Observations made while the bit during cutting was being cooled by a 7 MPa 'flat-fan' water jet that was directed across the width of the tungsten carbide bit insert indicated that the penetrating force of the bit could be reduced appreciably by the use of a water jet. Experiments were therefore designed to investigate and optimize this reduction in bit force.

The parameters that were assumed to be relevant to the decreased bit force and that were investigated during the test programme are the pressure of the water jets, the point of impingement of the water jets, and the number of jets directed at the interface between the rock and the bit. Coherent water jets were used throughout these experiments to give the maximum transfer of energy from the jets to the rock. A fixed flow rate of 30 l/min was used for the water jet since this was considered a practicable rate of flow in gold-mining stopes.

Laboratory Testing Equipment

Experiments were conducted in a test rig built to simulate an underground stope and to accommodate a full-size rockcutting machine for test cutting in a block

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of rock representing the stope face. This rig consisted of a stiff steel framework in the form of a hollow box, 6 m long and 3 m wide with a working height inside the box of 1 m (Figs. 1 and 2). The rock, 3 m long and 0,75 m square, was mounted on load cells that measured the forces acting on the bit in three orthogonal directions during cutting. The rockcutting machine was set up square against the rock and anchored by hydraulic jacks against the roof and floor of the box.

A double-acting linear rockcutting machine (Fig. 3) was used throughout the laboratory experiments. This comprises a strong main frame with anchoring jacks at

each end. A sliding member, the saddle, is mounted on cast-iron bearings on the main frame and is driven along the length of the frame by means of a double-acting hydraulic ram⁴.

The bit, which has been found to be the most satisfactory for cutting, incorporates two tungsten carbide inserts as the cutting element, which are brazed into the steel bit body (Fig. 4). This bit is mounted on a steel holder or blade, which in turn is attached to the machine saddle by means of a long feedscrew. Two assembled bits and blades are fitted to the rockcutting machine, one at each end of the saddle (Fig. 3). The bits are advanced

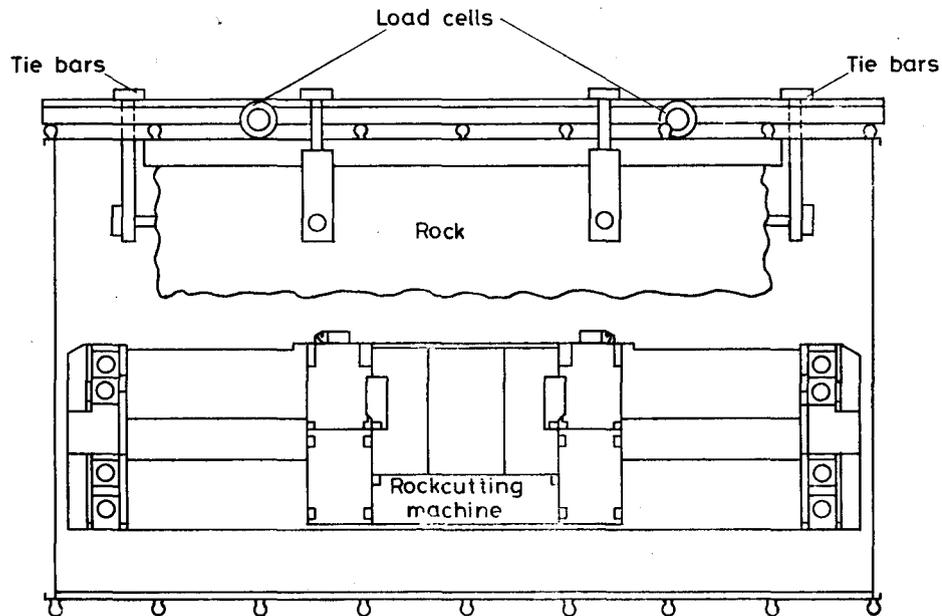


Fig. 1—Plan view of the test rig

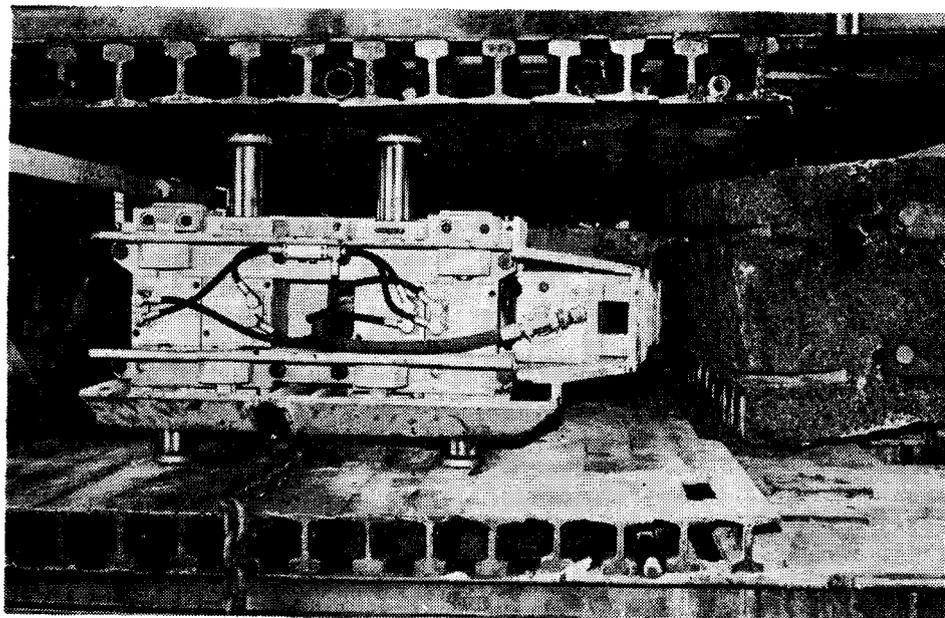


Fig. 2—Side view of the rockcutting machine in the test rig

into the rock by turning the feedscrew, this operation determining the depth of cut.

The rock used for all the laboratory tests was norite because quartzite, the country rock adjacent to the gold reefs, was unobtainable in the size of block required. Norite is a strong, basic, non-abrasive rock with a uniaxial compressive strength of approximately 300 MPa; quartzite is a strong, highly abrasive rock with a uniaxial compressive strength in the range 200 to 300 MPa and a quartz content of between 35 and 95 per cent. The indentation strength of norite is also comparable to that of quartzite. The major difference

between the two rock types is that, although they are rocks of essentially similar strengths, quartzite is far more abrasive, which is important from the viewpoint of bit wear. Therefore, these values provide justification for relating laboratory results involving force measurements in norite to the force required to cut unstressed quartzite in the underground mining situation.

The tests in which high-pressure water jets were directed towards the bit during the cutting were conducted with the standard pump normally used for high-pressure water-cleaning purposes. The water was conducted along a pipe inserted into the blade, and dis-

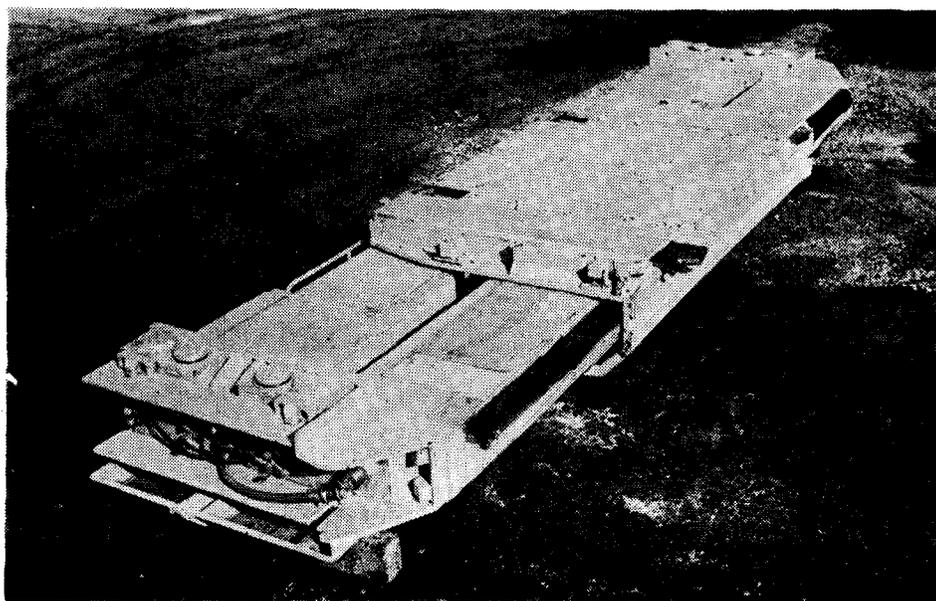


Fig. 3—The rockcutting machine

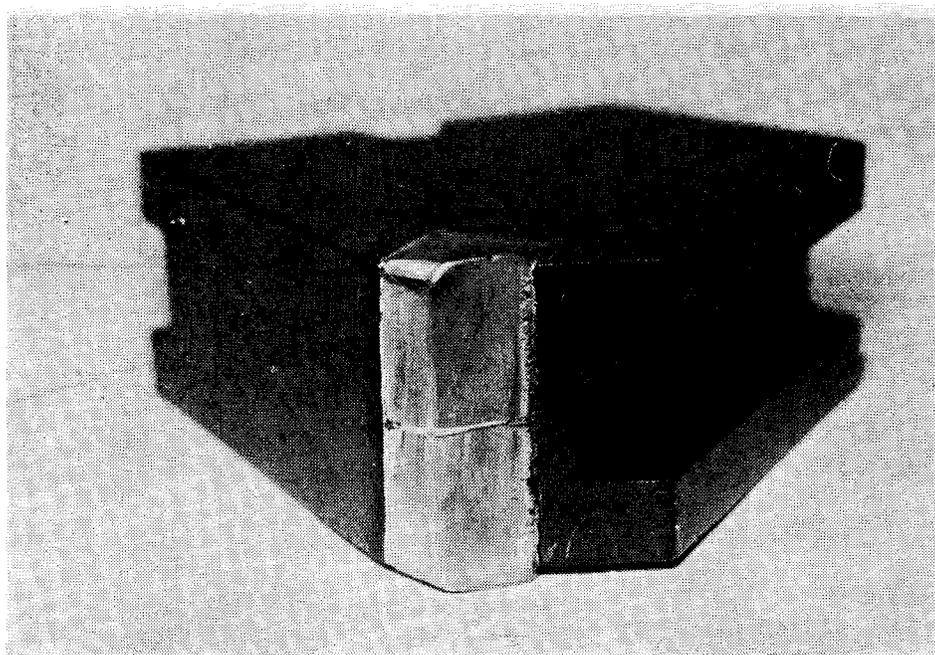


Fig. 4—The rockcutting drag bit

charged through nozzles mounted in the blade (Fig. 5). The nozzles used were similar to the design shown by other workers⁵ to form the most effective coherent jets at the pressures investigated during these experiments.

Experimental Procedure

The experiments conducted in the laboratory included measurements of the components of cutting force and penetrating force that act on the bit during the cutting operation (Fig. 6). The variables examined during these

tests were the effect of the pressure of the water jets and the importance of the point of impingement of the jets relative to the bit. In order that the mean values of the force measurements would be representative, ten cuts were made at a given depth of cut for each set of variables. This procedure was followed at various depths of cut up to the value at which the cutting force of the bit approached the maximum available force of the machine, which was approximately 150 kN. Graphs plotted from the results of these tests show the components of the

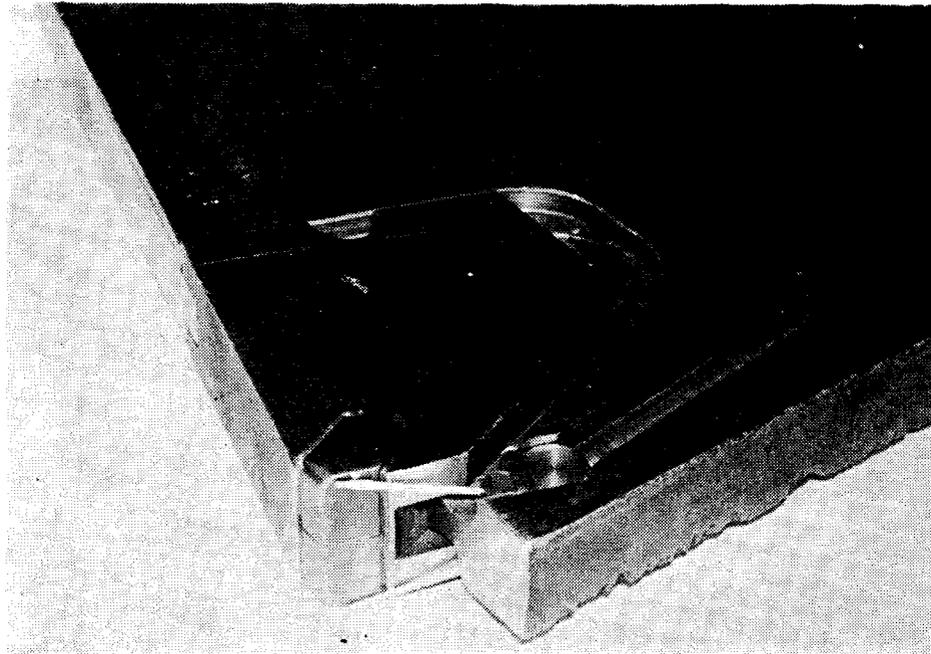


Fig. 5—The method of mounting nozzles in the blade. The white lines indicate the positions of the high-pressure water jets relative to the bit

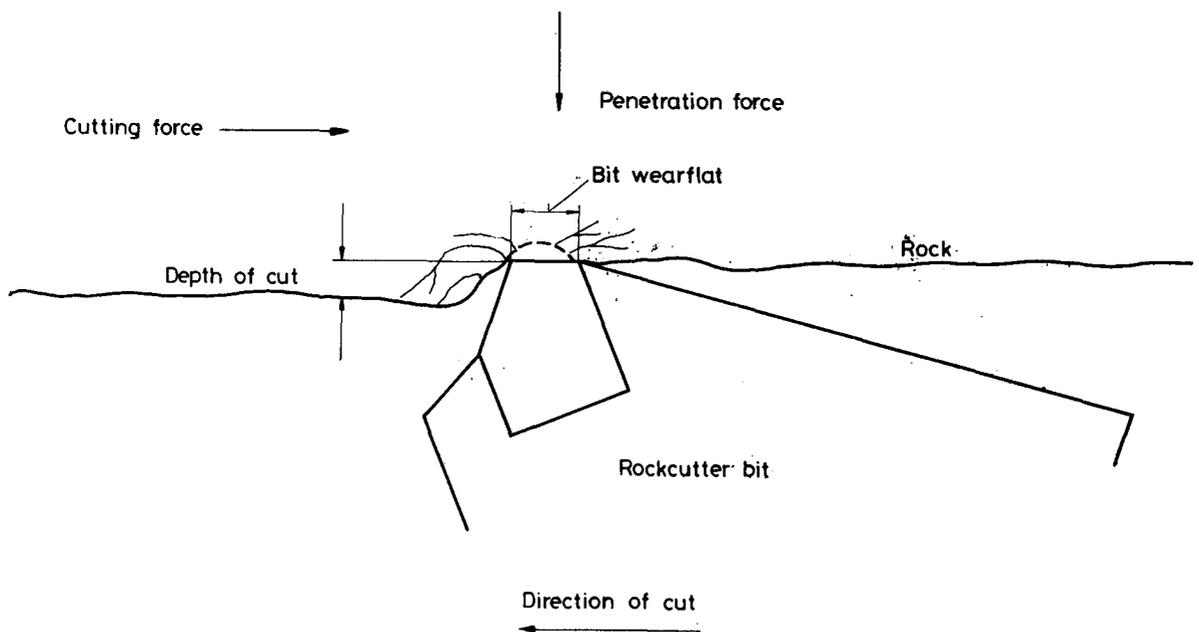


Fig. 6—Diagram of a bit cutting the rock, illustrating the components of the bit force

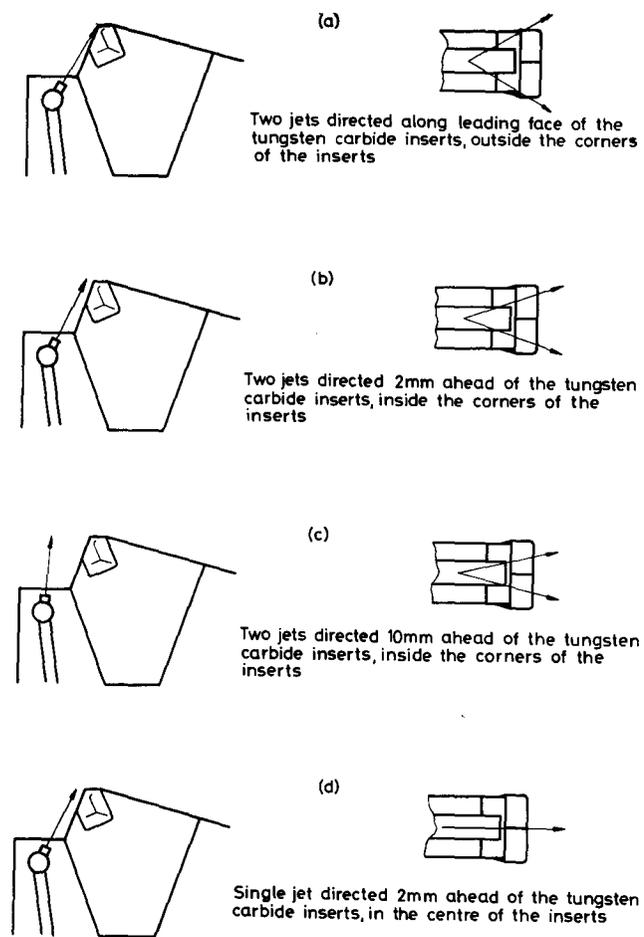


Fig. 7—Positions of the water jets relative to the bit

mean of the peak forces that were measured at the given depths of cut. Two points were plotted for each depth of cut, namely, the mean value for the peak force plus one standard deviation and the mean value for the peak force minus one standard deviation. The line that gave the best fit with the plotted data was then drawn.

Effect of Water Pressure

In experiments to investigate the influence of the pressure of the water jets on the bit force, the jets were directed outside the corners of the tungsten carbide inserts to impinge at the interface between the rock and the bit (Fig. 7a). Measurements of bit force were recorded when water jet pressures of both 10 MPa and 50 MPa were used with this nozzle configuration. The results were compared with the measurements of bit force, made in the same block of rock, when no high-pressure water jets were used. These results showed that there was a marked decrease of bit force at a given depth of cut when high-pressure water jets were used.

Effect of the Direction of the Water Jets

In order to show the importance of the direction of the water jets relative to the bit, an experiment was carried out with the nozzles aimed so that the jets impinged on the rock face approximately 2 mm ahead of the leading

edge of the tungsten carbide inserts. The included angle between the two jets was reduced so that the jets struck the rock inside the corners of the inserts of the bit (Fig. 7b). Measurements of the bit force were made while the water-jet pressure was 10 MPa. These were compared with the previous measurements of bit force (when water jets at the same pressure were directed outside the corners of the tungsten carbide inserts).

It was observed that the high-pressure water jets, at the pressures used for all these experiments, did no visible damage to the rock when they were traversed across the rock face without a bit. Although the mechanism involved in the cutting of rock with high-pressure water jets is not well understood, empirical methods have shown that, if appreciable damage is to be caused to the rock with continuous, non-cavitating water jets, the pressure of the jets should exceed the uniaxial compressive strength of the rock⁶. It is therefore to be expected that water jets at pressures of 50 MPa and less could not cause damage to the norite rock used during the laboratory experiments, since the norite has a uniaxial compressive strength of about 300 MPa. The marked reduction of the bit force when water jets at these pressures were used was not attributable, therefore, to pre-weakening of the rock by the jets, and must have resulted from an interaction between the jets and the fractured zone of rock close to the bit. Consequently, in order to show the size of the area ahead of the bit in which the water jets were serving to decrease the bit force, an experiment was conducted with two jets directed 10 mm ahead of the leading edge of the bit insert (Fig. 7c). The jets were directed onto the rock in the path of the wearflat of the bit insert. The pressure of the water jets for this test was 15 MPa.

The previous experiments had been conducted with the jets aimed at points close to the corners of the tungsten carbide inserts. These nozzle configurations were chosen on the assumption that the mode of rock fracture when a drag bit is used to cut strong rock is similar to that caused by a flat indenter⁷. It can be shown both mathematically and experimentally that severe stress concentrations are generated at the corners of a rigid punch pressed against a semi-infinite plate⁸. Therefore, the water jets were directed towards the corners of the bit in order to attack the areas of high stress. An experiment was conducted to test this hypothesis. A single water jet with a flow the same as the combined flow from the two jets used in the previous tests, namely 30 l/min at a pressure of 50 MPa, was directed towards the rock face along the centre of the tungsten carbide bit inserts, the jet being 2 mm ahead of the leading edge of the inserts (Fig. 7d). The results of this experiment were compared with the measurements of bit force when two water jets were directed, also at 50 MPa pressure, towards the corners of the tungsten carbide inserts.

Underground Experiments

In order to show the practical effect of water-jet-assisted cutting in the mining situation, five rockcutting machines at the Doornfontein trial site were fitted with the necessary equipment and the experiment was conducted underground. The pressure of the water jets

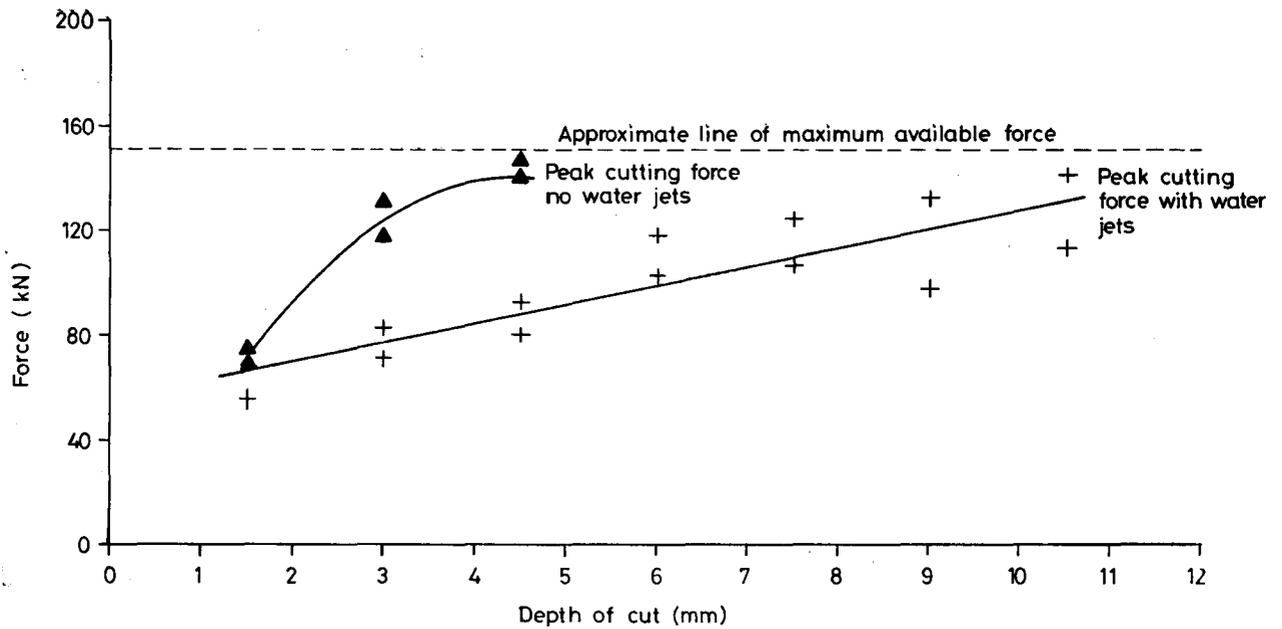


Fig. 8—Peak cutting force plotted against depth of cut when 50 MPa water jets were directed outside the corners of the tungsten carbide inserts in the bit

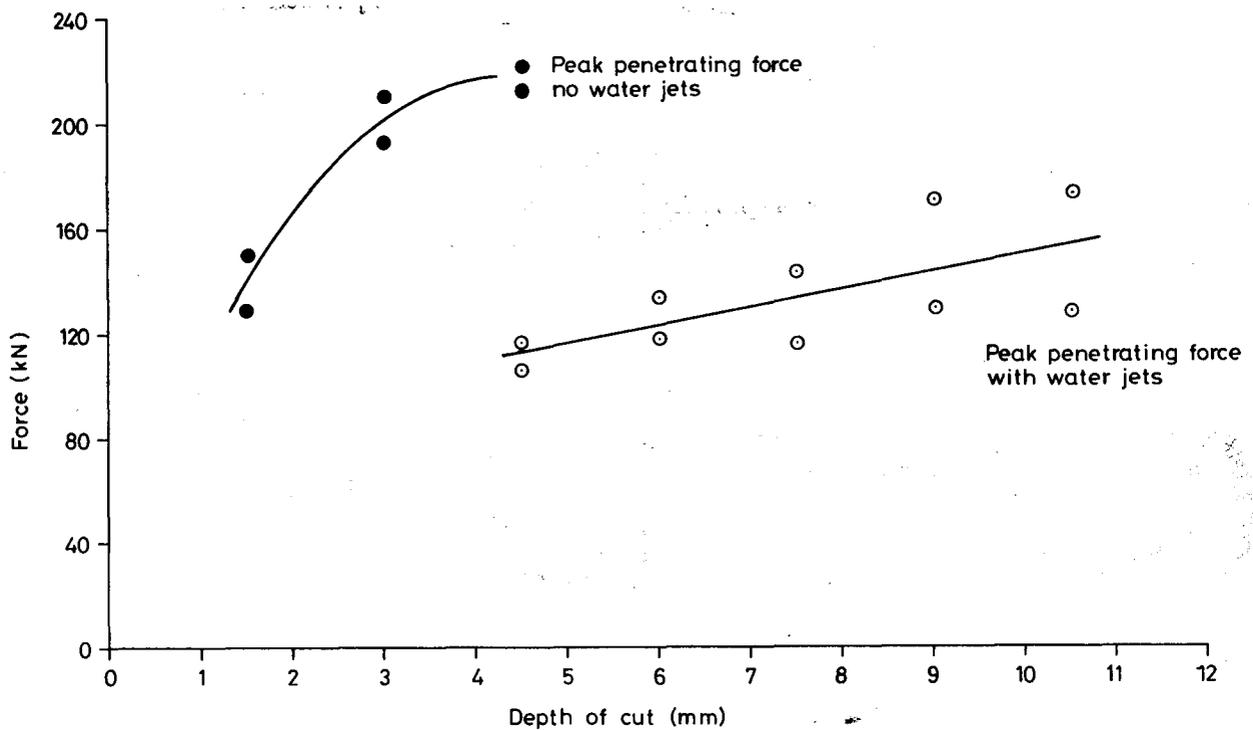


Fig. 9—Peak penetrating force plotted against depth of cut when 50 MPa water jets were directed outside the corners of the tungsten carbide inserts in the bit

used for these experiments was between 30 MPa and 40 MPa. The potential for increasing the depth of cut, and therefore the cutting rate of the machine, in fractured quartzite was investigated as part of this underground experiment. In addition, a study was made of the difference in the mode of failure between bits that had been used with high-pressure water jets and bits of a similar design that had not been used with high-pressure water jets.

Discussion of Results

Effects of Water-jet Pressure

A comparison was made between the components of the bit-cutting forces and those of the penetrating forces, both with and without the assistance of high-pressure water jets (Figs. 8 to 11).

Fig. 8 illustrates that the peak cutting force required is reduced substantially when 50 MPa water jets are directed towards the bit. The cutting force was reduced to the extent that the depth of cut was increased, for the same available machine force, from a maximum of 4,5 mm without high-pressure water jets to 10,5 mm maximum when jets were used. The penetrating force (Fig. 9) also was reduced markedly when the 50 MPa water jets were used. The maximum value of this force at a 10,5 mm depth of cut with high-pressure jets was the same as that without water jets at a 2 mm depth of cut.

The test conducted with 10 MPa water jets directed towards the bit also demonstrated a significant decrease in the values of cutting force required, compared with

those observed when high-pressure jets were not used (Fig. 10). The depth of cut was increased from a maximum of 4,5 mm with no water jets, to a maximum of 9 mm with the 10 MPa jets directed towards the bit. However, the penetrating force (Fig. 11) was not reduced to the same extent as was recorded when 50 MPa water jets assisted the cutting (Fig. 9).

Importance of Jet Impingement

An experiment to show the optimum position of the water jets relative to the corners of the tungsten carbide inserts in the bit was carried out with 10 MPa jets directed immediately ahead of the inserts. The two positions of the jets were outside the corners of these bit inserts (Fig. 7a) and inside the corners of the inserts in the path of the bit wearflat (Fig. 7b). The bit forces recorded during these tests are plotted against depth of cut in Figs. 12 and 13, which show that there was only a small change in the values of cutting force between the two nozzle configurations. The penetrating forces were consistently lower with the jets directed inside the insert corners in the path of the bit wearflat (Fig. 7b).

The extent of the area within which the water jets act to reduce the bit force was investigated when two 15 MPa jets were directed about 10 mm ahead of the leading edge of the tungsten carbide inserts (Fig. 7c). Measurements of bit force both with and without water jets directed onto the rock face during this test are plotted against depth of cut in Figs. 14 and 15, which show that there was no major reduction of bit force on the scale observed during the previous tests.

It was therefore demonstrated that, in order to be

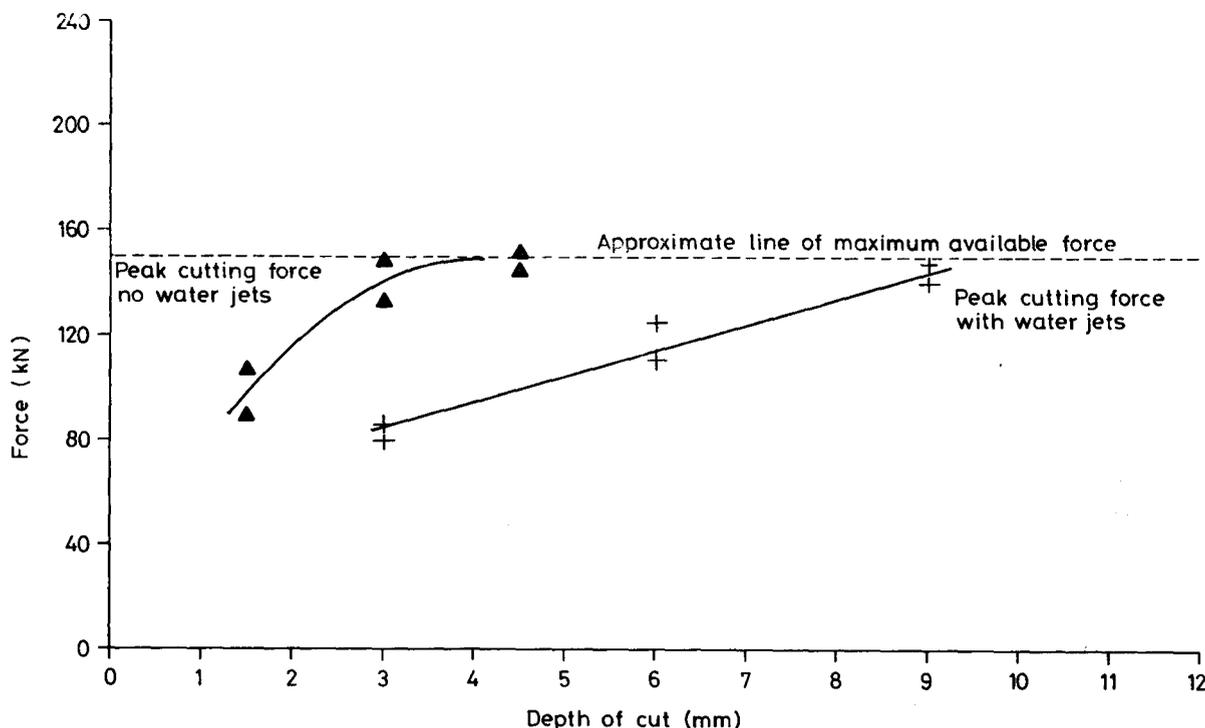


Fig. 10—Peak cutting force plotted against depth of cut when 10 MPa water jets were directed outside the corners of the tungsten carbide inserts in the bit

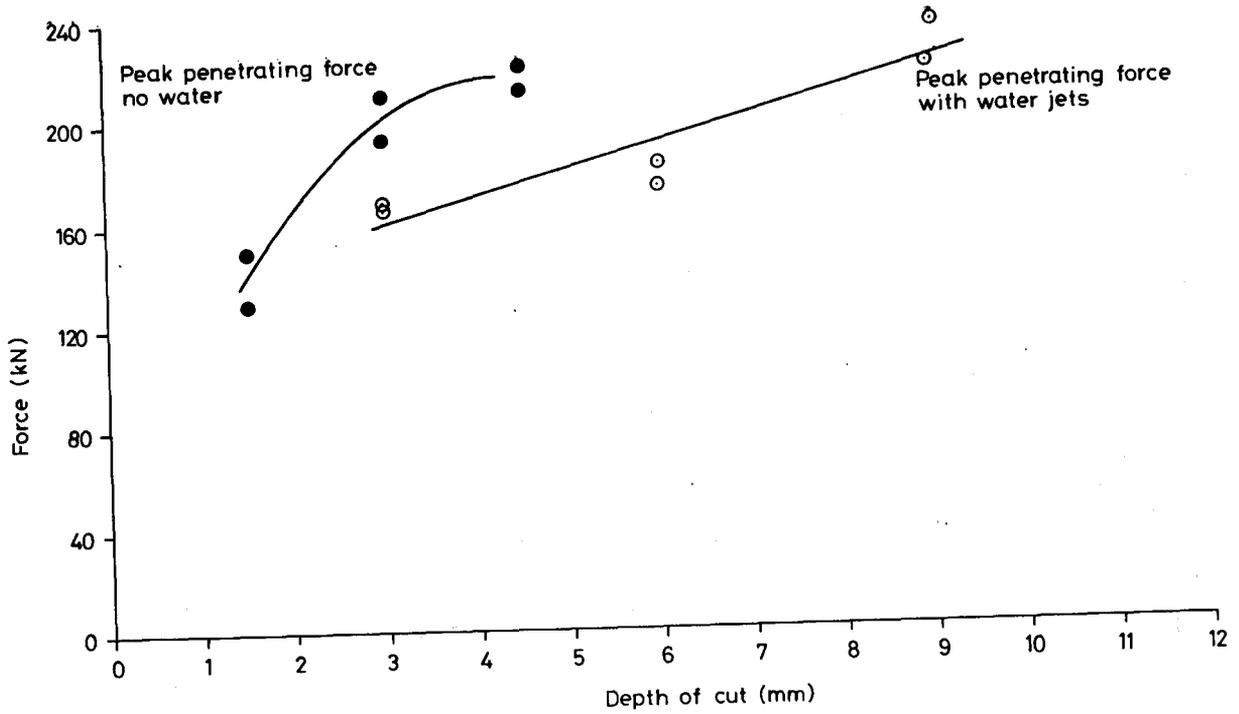


Fig. 11—Peak penetrating force plotted against depth of cut when 10 MPa water jets were directed outside the corners of the tungsten carbide inserts in the bit

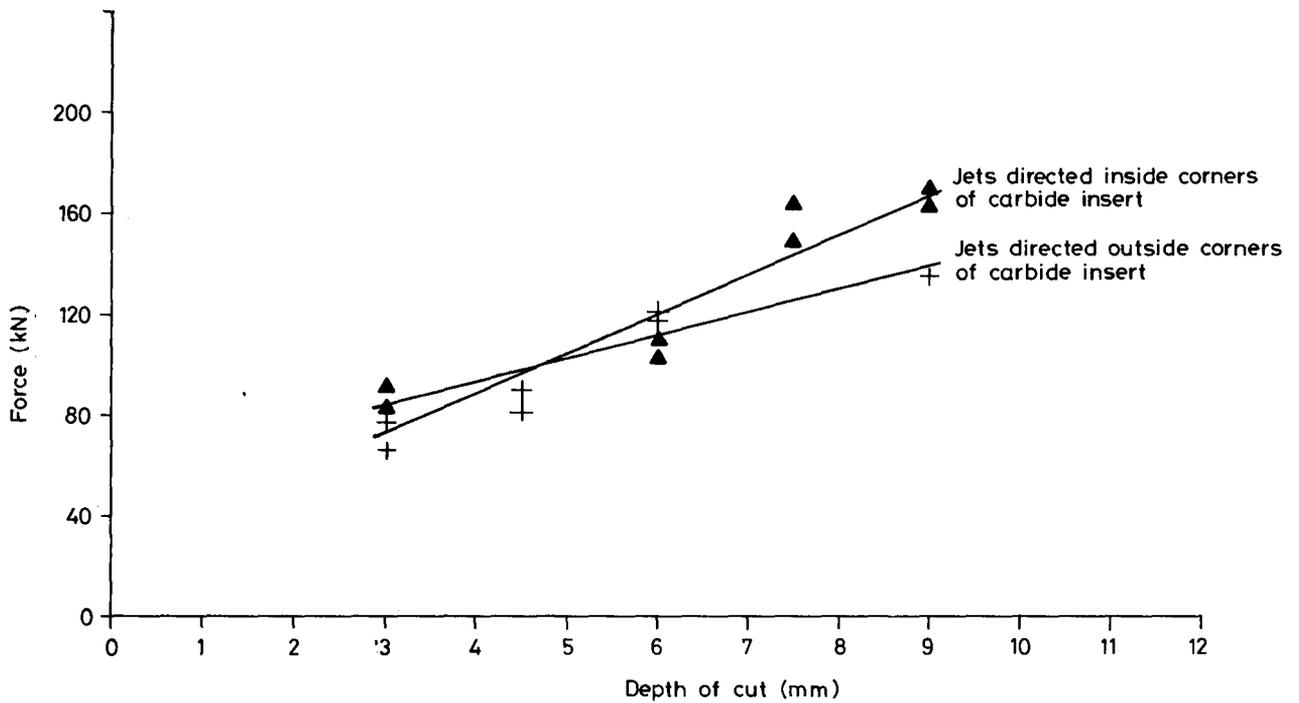


Fig. 12—Peak cutting force plotted against depth of cut when 10 MPa water jets were used. This graph compares the forces for jets directed outside the corners of the tungsten carbide inserts in the bit with the forces for jets directed inside the corners of the inserts

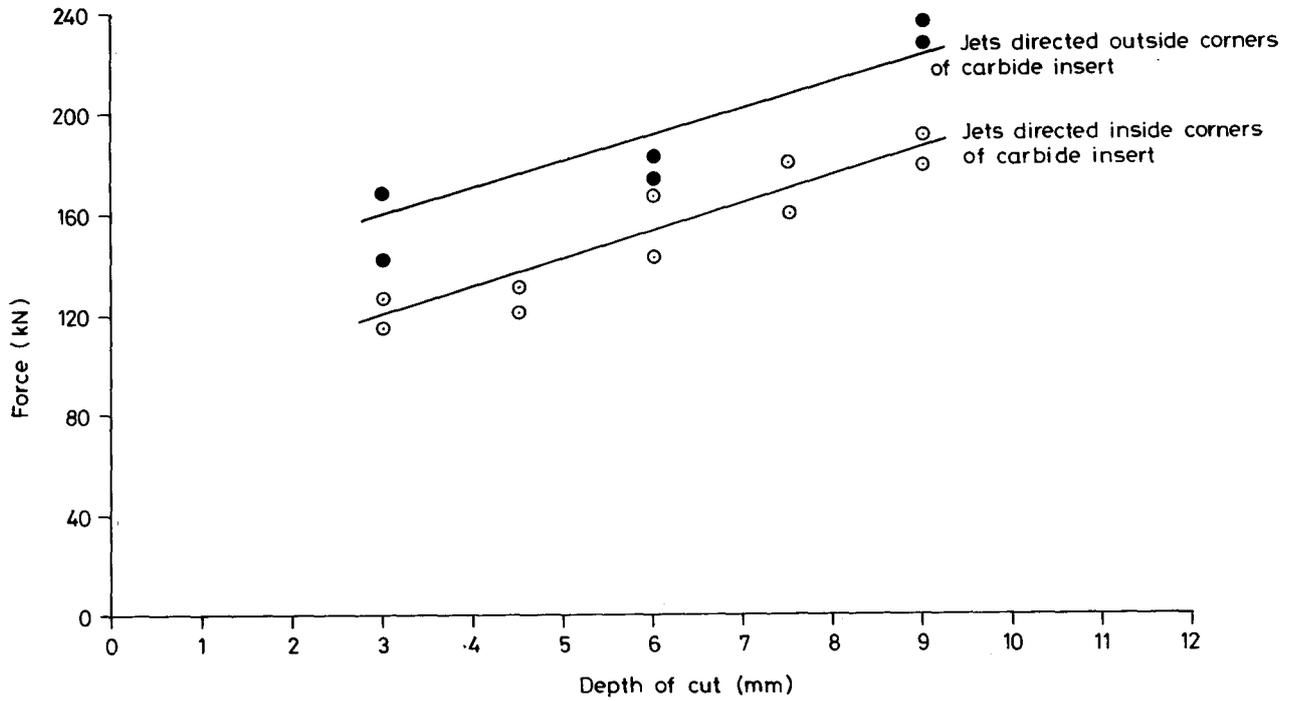


Fig. 13—Peak penetrating force plotted against depth of cut when 10 MPa water jets were used. This graph compares the forces for jets directed outside the corners of the tungsten carbide inserts in the bit with the forces for jets directed inside the corners of the inserts

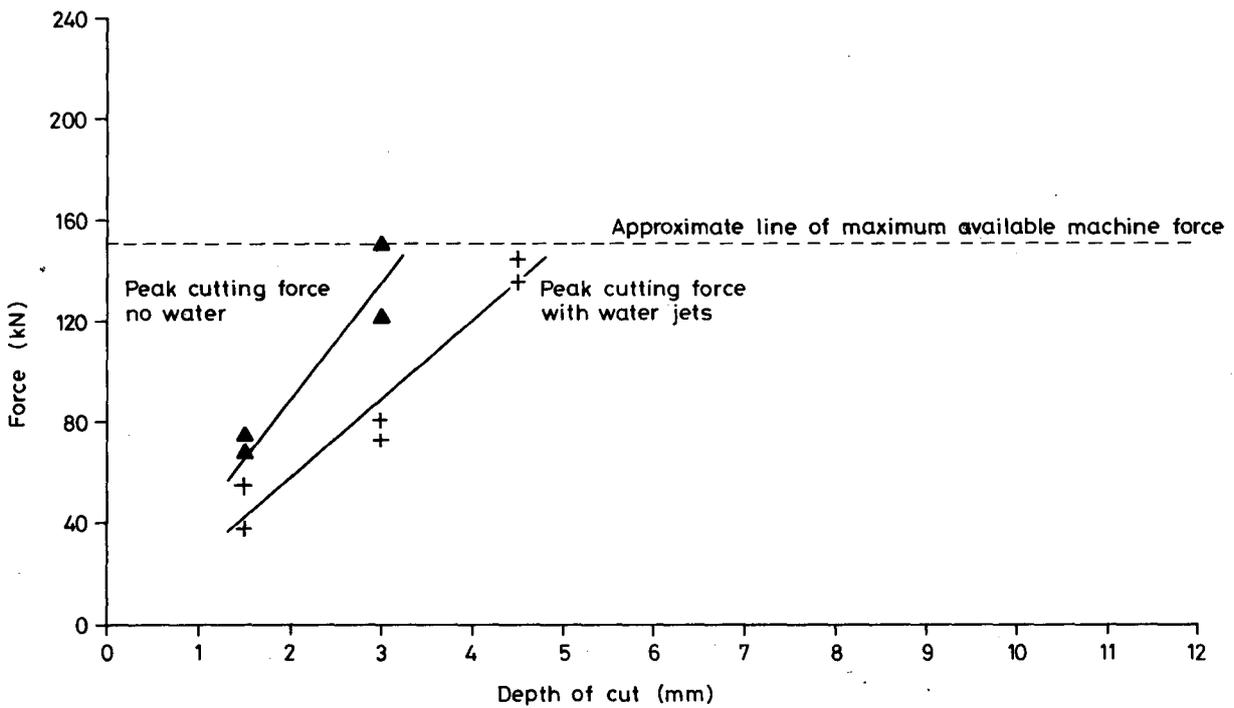


Fig. 14—Peak cutting force plotted against depth of cut when 15 MPa water jets were directed 10 mm ahead of the bit

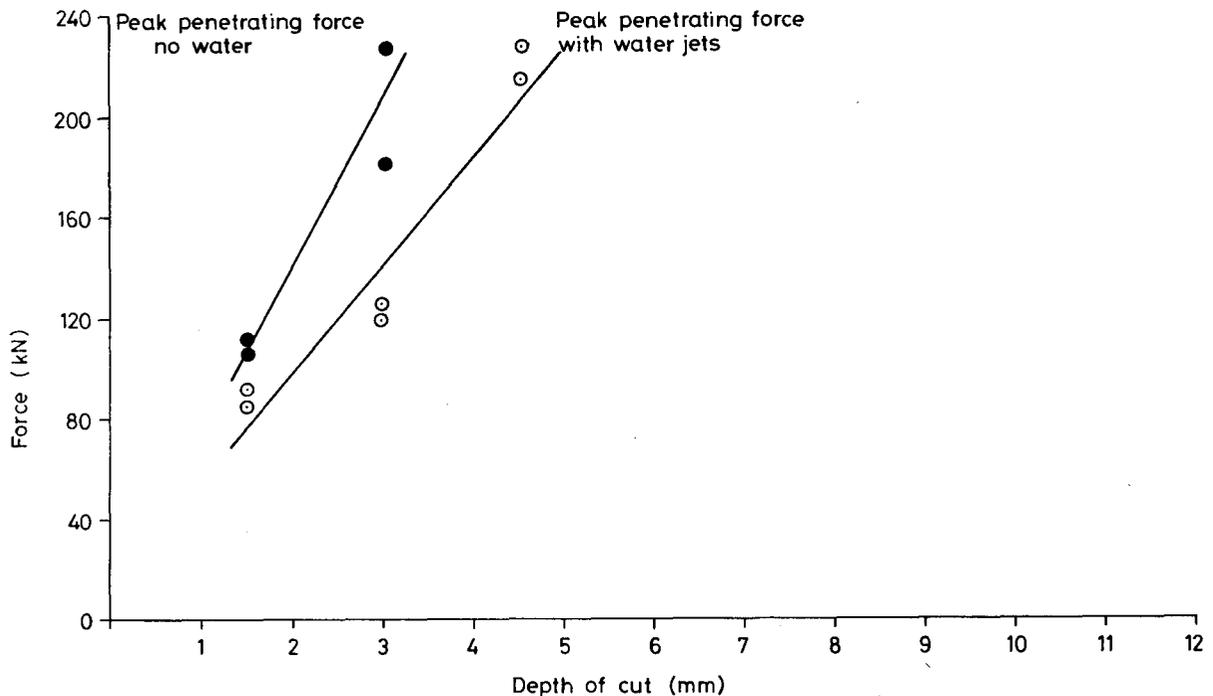


Fig. 15—Peak penetrating force plotted against depth of cut when 15 MPa water jets were directed 10 mm ahead of the bit

effective in reducing bit forces, the water jets have to impinge within a distance of less than 10 mm from the leading edge of the tungsten carbide bit inserts.

The results of bit-force measurements from the experiment to show whether the direction of the water jets towards the corners of the tungsten carbide inserts of the bit was more effective than a single jet at the centre of the interface between the rock and the bit are presented graphically in Figs. 16 and 17. These graphs show that values of penetrating force were much greater when the single jet was used, which tends to confirm the original hypothesis that the optimum point of impingement of the water jets is at the area of greatest stress, i.e. at the corners of the bit.

Underground Tests

The cutability of Witwatersrand quartzite, the country rock adjacent to the gold reefs, depends upon the quartz content of the rock and the degree of rock fracture caused by stress from mining at depth. The maximum depth of cut without water jets in relatively unfractured quartzite at the Doornfontein test site was typically 2 mm to 3 mm; when the water jets were directed towards the bit, this was increased to between 10 mm and 15 mm. In highly stressed, fractured ground, the maximum depth of cut without water jets was between 8 mm and 10 mm, which was increased to more than 40 mm when water jets were used. Thus, an average fivefold gain in depth of cut, and therefore in the instantaneous cutting rate, was achieved with the

assistance of high-pressure water jets during the underground tests.

The wear and failure pattern of the bits used for the tests underground also changed markedly when water jets were used. With no water jets, the majority of the bits were removed from service because of failure of the braze joint or fracture of the tungsten carbide insert. The mechanism causing these failures, although not completely understood, was probably initiated either by a high rate of heat transfer to the bit causing thermal deterioration of the braze joint and tungsten carbide, or by excess load causing shattering of the carbide during the cut. The appreciable cooling effect of the water jets, combined with the reduced bit force, decreased the braze and insert failures to the extent that bits were ultimately discarded because of bluntness caused by wear. An improvement in bit life in terms of the area cut per bit was also observed when water jets were used to assist the cutting. It is expected that bit life will be further improved by the use of harder grades of carbide. This would be made possible by the lower bit forces required when high-pressure water jets are used.

Conclusions

Laboratory and field experiments have shown that the force acting on a drag bit cutting strong rock can be reduced by the directing of coherent water jets at a moderately high pressure (50 MPa) immediately ahead of the bit during the cutting operation. During underground tests, the lower bit force resulted in a fivefold increase

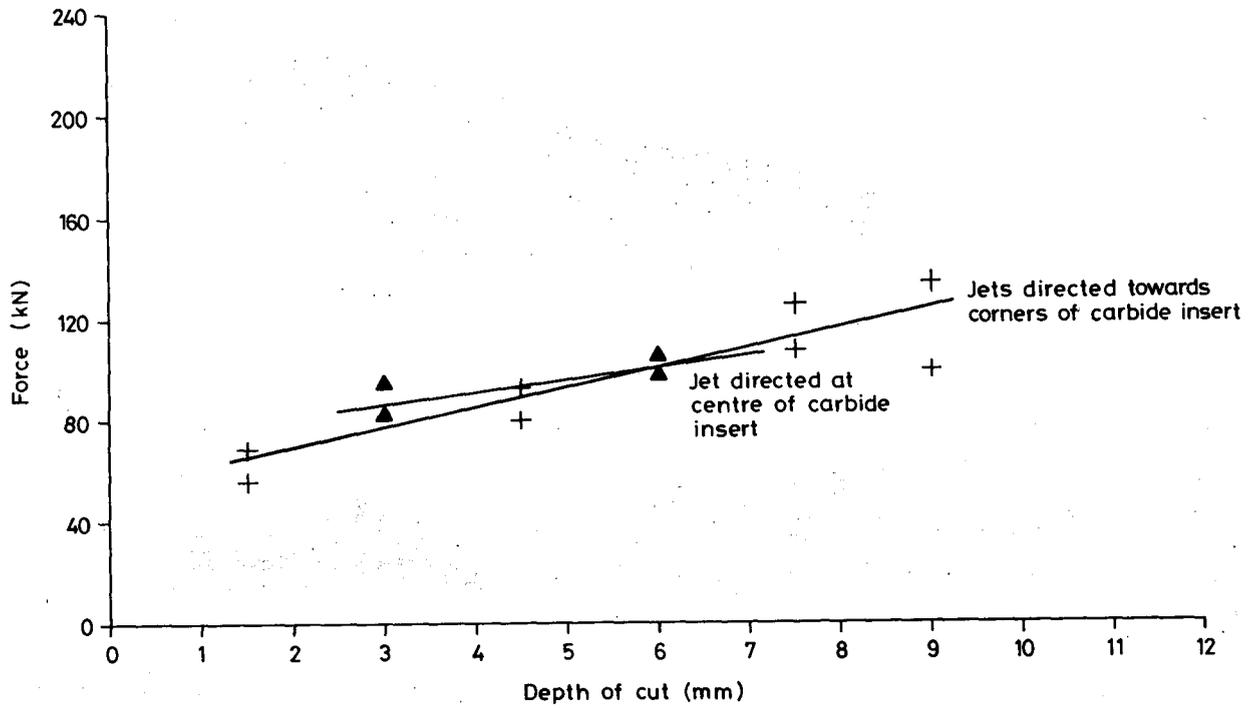


Fig. 16—Peak cutting force plotted against depth of cut when a single 50 MPa water jet was directed towards the interface between the bit and the rock along the centre of the leading face of the tungsten carbide inserts in the bit

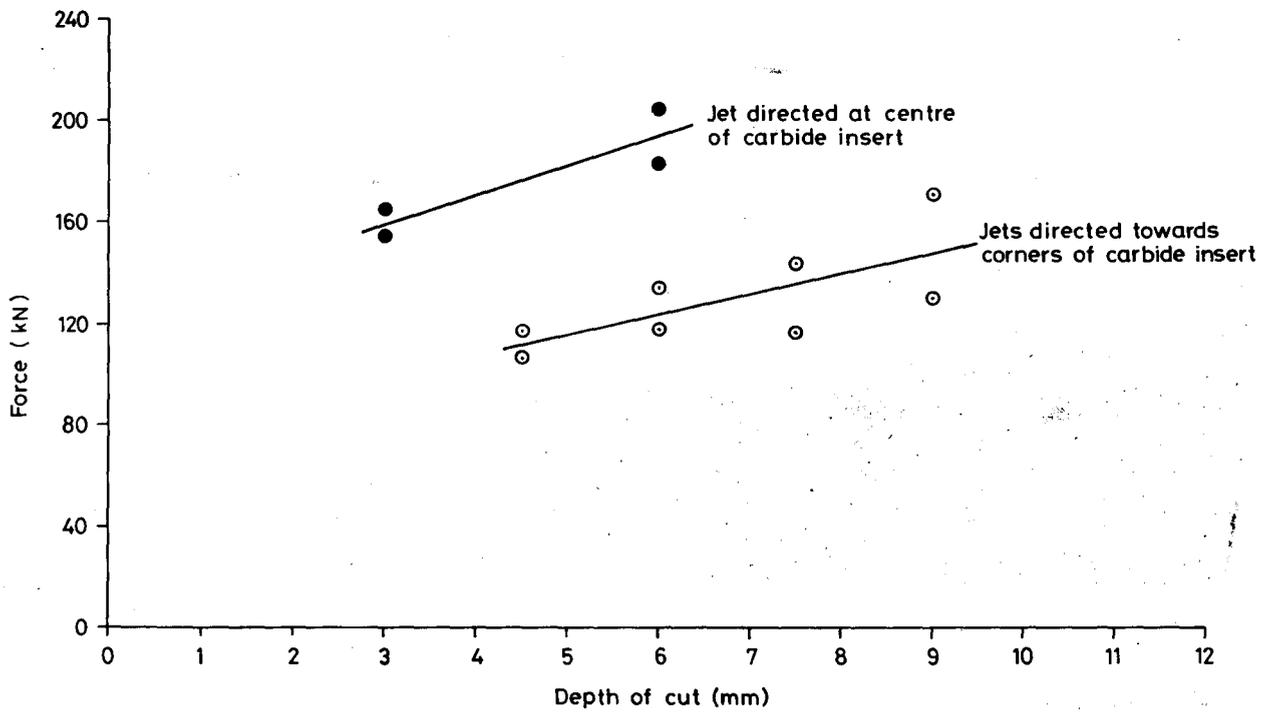


Fig. 17—Peak penetrating force plotted against depth of cut when a single 50 MPa water jet was directed towards the interface between the bit and the rock along the centre of the leading face of the tungsten carbide inserts in the bit

in the depth of cut in fractured quartzite. This beneficial effect of water jets was shown to be restricted to within a zone immediately ahead of the leading edge of the bit.

This discovery is likely to be of benefit to other methods of working strong rock in which a hard surface is applied to the rock to remove chips; for example, it may assist disc cutters in tunnel and raise-boring applications.

Acknowledgements

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