A method especially useful for cutting and breaking hard rock such as granite from the face of a tunnel is disclosed. A pattern of slots are cut into the rock face by directing a high velocity plasma jet on the rock face to melt a portion of the rock face and produce a molten film and applying electrical power to the plasma-jet and a cooperating electrode to flow electric current through the molten film to further heat the molten film and melt additional rock to form a slot. After the pattern of slots are formed, spaced plasma streams are introduced into the slots and electrical power of a frequency effective to produce dielectric heating in the rock is applied through the plasma streams to produce a heated region within the rock mass which thermally stresses and severs that rock mass portion into fragments.
METHOD OF ROCK CUTTING EMPLOYING PLASMA STREAM

SUMMARY OF INVENTION

This invention relates to methods for cutting and breaking hard rock and more particularly to methods especially useful for cutting and breaking hard rock such as granite from the face of tunnel. Boring a tunnel through hard rock has been done conventionally by drilling a number of holes into the tunnel face with percussive tools and then fragmenting the tunnel face by the detonation of explosives inserted into the drilled holes. The operation has been slow and has required expensive capital equipment. A technique has been developed for fragmenting rocks by dielectric heating, but it has been difficult to establish reliable electrical contact with the rock mass with the electrodes used and the positioning of the electrodes has been slow and cumbersome. Objects of the invention include the provision of methods permitting more rapid tunnelling and less expensive tunnelling through hard rock.

Another object of the invention is to provide novel and improved methods for cutting rock.

Another object of the invention is to provide a reliable, high speed method for hard rock cutting.

One aspect of the invention features the method of rock cutting, e.g. for extending a tunnel face through a rock face comprising the steps of cutting a pattern of slots into the rock face, each slot being cut by directing a plasma-jet on the rock face to melt a portion of the rock face and produce a molten film thereon, and applying electrical power to the plasma-jet and a cooperating electrode to cause electric current along a path that includes the plasma-jet, the molten film, and the cooperating electrode, thus further heating the molten film and melting additional rock underlying the molten film to form a cut in the tunnel face. The plasma-jet provides a gaseous contact electrode that facilitates maintaining the electrically conductive path between the power supply and the film of molten rock. The cooperating electrode may take a number of forms, for example it may be a graphite rod, a conductive metal rod, or a second plasma-jet may be employed. The nature of the power supply is a function of the characteristics of the rock to be cut and may be DC or AC or DC with a superimposed AC signal. It is preferred that the plasma-jet have a velocity in the order of at least three thousand feet per second. The dynamic erosive effects of this high velocity jet facilitates the cutting operation. When the cooperating electrode is formed by a second plasma-jet, that jet in a particular embodiment has a substantially lower velocity, preferably less than about 10 percent of the velocity of the other plasma-jet. It may also be desirable in particular cutting operations to modify the characteristics of the molten film by use of an additive such as an alkaline flux (e.g. sodium carbonate) with rock such as granite or an acid flux (e.g. potassium pyrosulfate) with rock such as basalt and such additive may be introduced to the molten film by means of the plasma stream. An auxiliary quench or ejection jet may be employed to facilitate removal of debris from the cut. Still another object of the invention is to provide novel and improved methods for fragmenting rock.

Another aspect of the invention features breaking off fragments of rock by directing a plurality of plasma streams into holes or slots spaced apart in a region of the rock mass to make electrical contact between the plasma streams and the rock faces contacted by the plasma streams, and then applying electrical power of a frequency effective for producing dielectric heating in the rock through said plasma streams to heat dielectricly the rock mass between the rock faces to produce a heated region within the rock mass and thermal stress cracks that sever the rock mass into fragments.

The plasma streams employed in this aspect of the invention are preferably of low velocity so that a large electrical contact area is provided at the bases of the spaced slots or holes. The applied dielectric heating power creates a heated core a substantial distance below the face of the rock mass so that greater amounts of rock are removed than would be the case where the heated core was nearer the surface.

The invention provides efficient methods for cutting and breaking rock. Other objects, features and advantages of the invention will be as seen from the following description of particular embodiments progresses in conjunction with the drawings in which:

FIG. 1 shows the invention applied to extending a tunnel face; FIG. 2 shows, at larger scale, cutting according to the invention with a pair of plasma streams being used to cut a slot into the rock of the tunnel face; FIG. 3 shows a fragmenting operation according to the invention employing the application of plasma streams to the tunnel face; and FIG. 4 shows a cross-section view through the center of a slot to reveal in greater detail aspects of the cutting method shown in FIG. 2.

DESCRIPTION OF PARTICULAR EMBODIMENTS

As shown in the drawing, tunnelling equipment 10 is brought up to face 12 of tunnel 14. Conventional support mechanism 16 supports torch holder 18 in position before tunnel face 12. According to the invention the advance of the tunnel face is accomplished in two operations successively applied. The first of these is a cutting operation shown more particularly in FIGS. 2 and 4. During the cutting operation, torch holder 18 supports primary plasma torch 20 and secondary plasma torch 22 in fixed relationship to each other with the plasma 24, 26 from each torch directed against the rock face 12 to form an elongated slot 28.

A suitable primary plasma torch 20 is shown diagrammatically in FIG. 4 and has a central tungsten cathode 32 supported by insulator 34 in cavity 36 within housing 38 that carries anode electrode 40. Anode 40 is water cooled and defines a nozzle passage 42. A conduit 44 connected to a supply 46 of inert gas such as argon communicates with cavity 36 to admit gas symmetrically thereto for flow past cathode 32 and out through nozzle 42. Pilot arc DC power supply 48 (which optionally may have a super-imposed high frequency, e.g. 10 kHz) is connected with its negative pole to cathode 32 and its positive pole to anode 40. One or more ports 50 into nozzle passage 42 provide a means for introducing an additive into plasma-jet 24. Conduit 52 is connected to ports 50 to deliver the additive to torch 30.

A suitable secondary plasma torch 22 is also shown diagrammatically in FIG. 4 and has housing structure 60 enclosing chamber 62 with a water cooled electrode 64 that defines an outlet orifice 66. Central electrode
A cutting operation is initiated by turning on the flow of inert gas (i.e., argon) which enters chamber 36 of torch 20 through conduit 44 and then passes out through orifice 42. DC power supply 48 is turned on, causing pilot arc 54 to form between cathode 32 and anode 40. The gas issuing from orifice is ionized by arc 54 to form a plasma. The gas pressure in chamber 36 is maintained at sufficient pressure so that a high velocity plasma-jet 24 issues from orifice 42. Typical velocities are in the range of 5,000 ft./sec. and above and preferably above 10,000 ft./sec. Plasma-jet 24 is initially directed at the rock face 12 until a portion of the rock is melted to form a molten film 80. The electrical conductivity of this molten rock is higher than that of the solid rock. Secondary torch 22 is put in operation by flowing argon gas through the torch and applying electric power from the power supply 72. Pilot arc 74 is established between the central electrode 68 and the electrode wall of orifice 66. The diameter of orifice passage 66 is greater than the diameter of orifice 42, passage 66 has greater length, and the pressure in chamber 62 is less than that in chamber 36 of primary torch 20 so that a relatively low velocity plasma stream 26 issues from torch 22. The plasma stream 26 from torch 22 is directed against and makes electrostatic contact with a portion of molten film 80 formed by the plasma jet 24 from primary torch 20. Power supply 84, which in a particular embodiment is a DC power supply of the welding type with a drooping characteristic, but which may provide AC or AC superimposed on DC depending on the particular application, is switched on and a transferred arc path 86 is established with the current passing along plasma arc 24, the molten rock 80 and plasma stream 26 which provides a return electrode for the current, conducting it back to torch 22 and to the power supply 84. A magnetic field usefully may be employed on electrode 64 to rotate the contact point of the main current carrying arc 86 in particular applications. The electric current passing through the film 80 of molten rock strongly heats the film so that additional rock underlaying the current path is melted. The high velocity jet 24 from torch 20 blows away material and thus enhances the rock cutting. Jet 88 (e.g., compressed air or a quench liquid) may be employed to facilitate removal of debris from the slot 28. After the rock cutting operation has been initiated, torches 20 and 22 are advanced in fixed relationship to each other by mechanism 16 across the face 12 of the tunnel to form the slot 28 in the face. Further slots are cut in the same manner to produce a pattern of slots penetrating into the face a distance which may typically be in the order of one foot or more.

After a pattern of slots is cut into the tunnel face as described above, the blocks of rock are fractured off the face. This is done with a pair of plasma torches 90, 92 as shown diagrammatically in FIG. 3. Apparatus for the cracking operation is shown in FIG. 3. Torches 90 and 92 are similar to torch 20 described above except they are constructed for lower velocity operation to produce a long gaseous plasma column that extends to the base of the hole or slot in the rock face. As the resistance of an argon column is in the range of 0.1 ohm cm., little power is dissipated in the gaseous electrode column. In particular applications, it may be advantageous to use more than two gaseous electrodes.

When in operation, torches 90 and 92 are supported in front of rock face 12 by torch holder 18. Suitable gas supplies, and power sources (diagrammatically indicated at 94) are connected to torches 90 and 92. Each of the torches 90 and 92 is put into operation in a manner essentially identical with that described above for torch 20. The plasma streams 96, 98 issuing from torches 90 and 92 are directed into two spaced slots of the pattern. Each of the plasma streams establishes electrical contact on the rock face of the slot along which it flows and its low velocity maintains an enlarged plasma environment at the base of the slot. The velocities of these streams should be in excess of twenty feet per second and velocities in the range of 100–200 feet per second are satisfactory in a particular embodiment. Electrical power of a frequency effective for dielectrically heating rock (e.g., a frequency in the general range of 0.5 to 20 MHz) is applied across the two torches 90, 92 and through the plasma stream conductors 96, 98 to the rock face adjacent to the plasma stream. The electric field applied across the rock (preferably at a voltage gradient in the range of 750–7,500 volts/ inch) produces a thermal “nugget” 100 in the center of the rock blocks which creates thermal stress and fragments rock from the face of the tunnel. The fragmenting process is repeated at new locations in the slot pattern, thus extending the tunnel face into the rock mass. After the face has been cleared by the fragmenting process, the cutting process is resumed to further advance the tunnel face.

As an example of the principle of transferred arc cutting of rock, a standard TAFCA Model 51 torch was connected to a 40 kW DC, 160 volt open circuit power supply. The torch had a nozzle diameter of one-quarter inch and was located approximately ½ inch above the face of a granite rock mass. A graphite rod was employed as the secondary or return electrode. Once the non-transferred arc was turned on and the rock became molten, the arc appeared to conduct through the molten material to the graphite rod. Typical operating parameters were:

| DC volts | 90 |
| DC amps | 400 |
| Argon, gas flow (SCFH) | 110 |

The jet velocity used during these tests was in the range of 5,000 fps. The cutting speed was about 2 inches per minute and over 5 cubic inches of rock were removed per kWh consumed.

Thus it will be seen that the invention provides techniques employing one or more gaseous electrodes for cutting and/or breaking hard rock. While particular embodiments of the invention have been shown and described, various modifications thereof will be apparent to those skilled in the art and it is not intended that the invention be limited to the disclosed embodiments or to details thereof, and departures may be made therefrom within the spirit and scope of the invention as defined in the claims.

What is claimed is:
1. The method of extending a tunnel face through a rock mass comprising the steps of cutting a pattern of slots into said tunnel face, each slot being cut by a method including directing a primary plasma stream from a primary plasma torch to impinge on the tunnel face, melting with said primary plasma stream portion of rock of the tunnel face to produce a molten film thereon, contacting said molten film with a cooperating electrode, and applying electrical power to said torch and cooperating electrode to cause current to flow along a path that includes said primary plasma stream, said molten film, and said cooperating electrode to further heat said molten film and melt additional rock underlying said film to form a cut in the tunnel face, and breaking off from the tunnel face fragments of rock between said slots, said fragment being broken off by a method including directing a first plasma stream against a first region of said rock mass at the bottom of a first slot cut in said tunnel face to make electrical contact between said first plasma stream and a first rock surface, directing a second plasma stream against a second region of said rock mass at the bottom of a second slot spaced from said first slot to make electrical contact between said second plasma stream and a second rock surface, and applying a voltage of a frequency effective for producing dielectric heating in said rock across said first and second plasma streams to said first and second rock faces to dielectrically heat a portion of said rock mass between said first and second rock faces to thermally stress and sever said rock mass portion into fragments.

2. The method as claimed in claim 1 wherein said primary plasma stream has a velocity in the order of at least three thousand feet per second.

3. The method as claimed in claim 1 wherein said cooperating electrode is a gaseous plasma stream.

4. The method as claimed in claim 3 wherein the velocity of said cooperating plasma stream is less than about 10% of the velocity of said primary plasma stream.

5. The method as claimed in claim 1 wherein said primary plasma stream has a velocity substantially greater than the velocities of said first and second plasma streams.

6. The method as claimed in claim 1 wherein the voltage applied across said first and second plasma streams and said rock mass portion has a gradient in the range of 750–7,500 volts/foot.

7. The method as claimed in claim 1 and further including the step of subjecting said molten film to a fluid jet to remove material from said cut.

8. The method as claimed in claim 1 and further including the step of introducing an additive to said molten film to modify the characteristics thereof.

9. The method as claimed in claim 8 wherein said additive is introduced to said molten film via a plasma stream.

10. The method for cutting rock comprising the steps of energizing a primary plasma torch to generate an elongated plasma stream, directing said elongated plasma stream to impinge on the rock, melting a portion of the rock with said elongated plasma stream to produce a molten film thereon, providing cooperating electrode means adjacent said molten film and in said elongated plasma stream at a point beyond said molten film so that said plasma stream extends along said molten film between said primary torch and said cooperating electrode means, and applying electrical power to said elongated plasma stream and cooperating electrode means to establish a transferred arc through said plasma stream between said primary torch and said cooperating electrode means to cause electrical current to flow along a path between said primary torch and said cooperating electrode means through said plasma stream to further heat said molten film and additional rock underlying said molten film to form a cut in the rock.

11. The method as claimed in claim 10 wherein said cooperating electrode means is a gaseous plasma stream and said cooperating plasma stream is directed to impinge on said molten film.

12. The method as claimed in claim 10 wherein said primary plasma stream has a velocity in the order of at least three thousand feet per second.

13. The method as claimed in claim 10 and further including the step of subjecting said molten film to a fluid jet to remove material from said cut.

14. The method as claimed in claim 10 and further including the step of advancing said primary plasma torch and said cooperating electrode means in a fixed relationship to one another to extend said cut and form a slot through said rock.

15. The method as claimed in claim 10 and further including the step of introducing an additive to said molten film to modify the characteristics thereof.

16. The method as claimed in claim 15 wherein said additive is introduced to said molten film via a plasma stream.

17. The method as claimed in claim 16 wherein said primary plasma stream has a velocity in the order of at least three thousand feet per second, said cooperating electrode means is a gaseous plasma stream and said cooperating plasma stream is directed to impinge on said molten film and the velocity of said cooperating plasma stream is less than about 10% of the velocity of said primary plasma stream.

18. The method as claimed in claim 17 and further including the step of subjecting said molten film to a fluid jet to remove material from said cut.

19. The method as claimed in claim 17 and further including the step of advancing said primary plasma torch and said cooperating electrode means in a fixed relationship to one another to extend said cut and form a slot through said rock.

20. The method of breaking off rock fragments from a mass of rock comprising the steps of directing a first plasma stream from a first torch against the surface of a first region of said rock mass to make electrical contact through said first plasma stream between said first torch and said first region, directing a second plasma stream from a second torch against the surface of a second region of said rock mass to make electrical contact through said...
second plasma stream between said second torch and said second region, said first and second regions being spaced one from another, and applying AC voltage of a frequency effective for producing dielectric heating in said rock across said first and second plasma streams and the rock mass between said spaced regions to dielectrically heat a portion of said rock mass between said spaced regions to thermally stress and sever fragments from said rock mass.

21. The method as claimed in claim 20 wherein the voltage applied across said first and second plasma streams and said rock mass portion has a gradient in the range of 750–7,500 volts/inch.

22. The method as claimed in claim 20 wherein the velocity of each of said plasma streams is in excess of 20 feet per second.

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UNITED STATES PATENT OFFICE
CERTIFICATE OF CORRECTION

Patent No. 3,788,703 Dated January 29, 1974

Inventor(s) Merle L. Thorpe

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 4, line 22, change "secnd" to --second--.
Column 4, line 57, after "consumed" insert a period.
Column 6, line 13, "are" should be --arc--.

Signed and sealed this 21st day of May 1974.

(SEAL)
Attest:
EDWARD M. FLETCHER, JR. C. MARSHALL DANN
Attesting Officer Commissioner of Patents
UNITED STATES PATENT OFFICE
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