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Experimental study for the process of the borehole thermal reaming by means of the angular plasmatron

Oleksii Voloshyn[1,*], *Iryna* Potapchuk[1], *Volodymyr* Yemelianenko[1], *Mykola* Zhovtonoha[2], and *Vitalii* Pertsevyi[2]

[1]Institute of Geotechnical Mechanics named by N. Poljakov of National Academy of Sciences of Ukraine, 49005, Dnipro, Simferopolska Str., 2a, Ukraine
[2]Dnipro National University of Railway Transport named after Academician V. Lazaryan, 49010 Dnipro, Lazaryana Str., 2, Ukraine

Abstract. Full-scale experimental study of the rock spallation by means of plasma jets is carried out. The aim of the experimental study was the measurement of the thermal power of plasma, weight of the rock spalls and duration of the plasma jets influence on the borehole surface. For the weight measurement of the rock spalls VT-200 analytical balance was used. In experimental study plasma jets flow out directly into the borehole of the granite block. The borehole and nozzles parameters of the plasmatron are complied with geometrical similarity. Experimental data are processed in the form of the energy consumption dependence of the thermal reaming of the borehole from the duration of the thermal treatment of the borehole surface. The results of the study could be applied to the borehole drilling processes.

1 Introduction

At present time problems related to the spallation and destruction of materials are of most interest [1-4].

In a modern mining thermal spallation reaming of the rock is used for a quarry extraction, forming of cavities and stimulation of oil and gas boreholes [5-8].

The processes of the thermal reaming are used in other branches of engineering and industry.

In particular, a task of mathematical models development of the thermal reaming and determination of term of safe exploitation of thermal barrier coatings that are used for manufacturing of turbine blades, combustion chambers of turbo-engines, pipes of the boilers and other equipment is urgent [9-11].

Application of theoretical and experimental investigations of thermal destruction of the rock by spallation is useful also for problems solving in aerospace industry, in particular, for mathematical modeling of ablation processes during supersonic plasma jet interaction with the surface of solid bodies [12].

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[*] Corresponding author: OIVoloshyn1951@nas.gov.ua

The relevance of application of thermal methods for rock destruction is based on the wide range of facilities for realization of the heating or cooling processes of rock.

Forms of thermal influence on the rock have the unified physical basis, namely, change of power connections potential [13].

Tensions of thermal expansion of rock minerals are proportional to the thermal expansion coefficient of minerals, Young's modulus and heating temperature.

Since Young's modulus and thermal expansion coefficient of rock minerals take different values, while heating inside the rock minerals besides tensions, predefined by the emergence of temperature gradient, the structural thermal tensions appear, that reach maximal values on the edges of mineral grains.

Therefore most of thermal rock destruction products detach from the rock mass along the grain edges of minerals [14].

In the cases of application of thermal methods of rock destruction the destruction products detach from the rock mass under the influence of the shear and tensile thermal stresses.

It is known that the strength limit for shearing and stretching is approximately 7-10 times less than the strength limit for the compression.

Therefore a thermal method of rock destruction is the most energy saving method of destruction [15].

While temperature increasing in a heating area along with the strength and aggregate hardness decreasing there is a reduction of rock fragility emerges that allows to use the thermal methods of rock destruction effectively not only in the processes of the borehole drilling but also in the processes of the boreholes reaming [16-18].

Most effective amid the processes of the borehole reaming are the thermal ones, in particular with application of the gas jet heating of rock with usage of arc electrical discharge.

Plasma burners have some advantages:

- widened adjustment range of thermal parameters and concentration of the jet power [19];
- diminished amount of hazardous gases emission [19];
- simplified system of the burners automation [20].
- fissure propagation at significant depth of the rocks in the process of their thermal destruction [20];
- higher values of the heat transfer coefficient and specific heat flux from the heat-transfer medium to the borehole surface [21].

It should be noted that efficiency of thermal fragile rock destruction increases due to rock hardness augmentation and expenditures of this process realization tend to diminish.

The highest efficiency of thermal method for rock destruction is reached in the borehole reaming process in a monolithic enough and well-drillable rock mass.

A common feature of the known options of technical decisions related to the application of the thermal tools with an arc electrical discharge for rock destruction is a stream of low temperature plasma that outflows from one or several nozzles in parallel or at an angle to the borehole axis.

Majority of the known experimental investigations concern the determination of time and temperature values of rock destruction.

In particular, in reference [22] for slot cutting plasma burner was used with thermophysical parameters of the torch as follows: efficiency temperature of the plasma torch 4000-7000 °C; maximal specific heat flux $1.2 \cdot 10^7$ W/m^2; heat transfer coefficient – up to 14 MW/(m$^2 \cdot$K).

The effect of the plasma burner application in the process of the thermal drilling was the formation of cracks up to 0.1 mm, that spread to considerable distance (1.2 cm and further) from the drilling channel.

In the reference [23] plasmatrons with the power within the range 25-30 kW were used for the heating of the borehole surface. Distance from the nozzle to the borehole surface was 20 mm, heat flux of the plasma jet was within the range $(5.82\text{-}11.64)\cdot 10^7$ W/m^2, temperature of the plasma jet was 4000 K.

In the reference [24] experimental study of the reaming process by means of plasmatron was executed for the borehole with initial diameter 60 mm. Plasmatron power was within the range 30-65 kW. Air consumption is within the range 0.005-0.010 kg/s. Mass-averaged temperature of the plasma flow was within the range 3000-4000 K. Air pressure at the level of 0.35 MPa provides the supersonic outflow mode of the plasma. Specific heat flux at the borehole surface was within the range $1.4\text{-}2.64\cdot 10^4$ kW/m^2.

Velocity of the reaming device inside the borehole was in the range of 3-8 m/hr.

Aiming the reduction of the concentration of nitrogen oxides in gases released from plasma jet and increasing of efficiency of energy transmission to rock, it is suggested to apply an open electric arc [25].

It will allow to intensify a heat exchange by radiation, as a temperature on the arc axis will reach 5000-10000 K.

In the spectrum of arc radiation approximately 50 % constitutes infrared radiation.

In the process of experimental investigation electric current of arc changed within the range of 90-150 A, air consumption was within the range of 1-3 m^3/hr, specific heat flux was 1 MW/m^2.

A method of the application of combustion chamber that provides increasing of thermal efficiency of plasma jet and reduction of nitrogen oxides content in a jet is known [26].

Parameters of the plasmatron for this purpose are shown in the Table 1.

Table 1. Parameters of the plasmatron.

Parameter	Value
Power, kW	1200-1600
Discharge power, kW	300-600
Air consumption, kg/s	0.3-0.4
Mass-averaged jet temperature, K	2500-2900
Mass-averaged velocity of the jet outflow, m/s	1000-1500
Thermal efficiency	0.7-0.8

The results of experimental investigation of plasma method of thermal borehole reaming from an initial diameter 100 mm to 500 mm on a depth up to 70 m is known [27].

The operating parameters of plasmatron are shown in the Table 2.

Table 2. Parameters of the plasmatron.

Parameter	Value
Power, kW	140-180
Compressed air pressure, MPa	0.4-0.5
Air consumption, m^3/s	0.04-0.06
Water pressure for cooling of electrodes, MPa	0.8-1.0
Water consumption, m^3/s	0.65

Parameters of the thermal reaming of the borehole by the case of quartzites are shown in the Table 3.

Results of the known experimental study [28] of the boreholes thermal reaming by means of plasmatron are presented in the Table 4.

Accordingly to the experimental study [29] in case jets of combustion products move parallel down the borehole axis, heat transfer coefficient is within the range 102-

103 W/(m^2·K), period of the spalls detachment is within the range 1-100 s, their thickness is within the range 0.5-0.7 mm.

Table 3. Parameters of the thermal reaming.

Borehole diameter after the thermal reaming, mm	Duration of the thermal reaming process, hr	Productivity of the thermal reaming process, m/hr	Plasmatron power, kW	Air consumption, m^3/min
350	53	0.85	132	1.6
330	47	0.96	130	1.6
350	47	0.96	130	1.6
340	43	1.04	132	1.6
330	41	1.09	129	1.6

Table 4. The results of the experimental study.

Parameter	Value		
	Quartzites	Magnetite-amphiboles	Magnetite-amphibole-silicates
Plasmatron power, kW	170-175	150-160	150
Initial borehole diameter, mm	105		
Borehole diameter after reaming, mm	450-500	270-320	230-250
Velocity of the plasmatron nozzle in a borehole, m/hr	1.0	1.0	0.7
Initial temperature of the heat transfer medium, °C	No data	No data	950-1000
Initial specific heat flux from the heat transfer medium to the rock surface, W/m^2	No data	No data	(8.4-9.5)·10^5

During the study of the thermal reaming process it was determined that micro cracks appearance occurs when heating temperature of the fine-grained hard rocks reaches 700-800 °C while for the large-grained hard rocks the heating temperature should be within the range 500-600 °C.

Micro cracks destruct the layer heated up to the temperature of destruction. If the thickness of the heated layer becomes larger than the grains size spalls tend to detach.

Thus, disseminated rocks are subjected to destruction at the temperature 700-900 °C into the thin spalls during rapid heating (1-2 s). Coarsely disseminated rocks are subjected to destruction at the lower temperature values into the thicker spalls and it takes larger time period.

Comparison of the technological parameters of the hard rock thermal reaming process (f=16-20) is shown in the Table 5 [29].

Parameters of the tests of the borehole thermal reaming by means of supersonic flame jet are shown in the Table 6.

2 Methods

In experimental study of the borehole thermal reaming by means of an angular plasmatron energy efficiency of the rock spallation process in comparison to that process operated by mean of axial plasmatron was investigated.

Experimental pattern for the thermal reaming of the borehole within the granite block by means of tangential plasma jets is shown in Figure 1.

Table 5. Comparison of the technological parameters of the hard rock thermal reaming process.

Drilling type	Overall power, kW	Borehole diameter, mm	Specific power, kW·hr/dm^3	Volumetric productivity, dm^3/hr
Roller-bit drilling	386	250	1.57	245.4
Flame jet drilling (oxygen)	700	180-220	1.5-3.4	204-456
Flame jet reaming (air)	1000	400-500	0.7	1256-1964
Flame jet drilling (air)	1000	200	5-6	200-220

Table 6. Parameters of the tests of the borehole thermal reaming by means of supersonic flame jet.

Parameter		Units	TBV-1000	TBV-1500
Initial borehole diameter		mm	250	220
Diameter of the reamed borehole		mm	320-440	360-500
Borehole depth		m	19	19
Consumption	kerosene	m^3/hr	1920	2458
	water	kg/hr	100	130
Jet temperature		°C	1100	1450
Average reaming productivity		dm^3/hr	500	900

Fig. 1. Experimental set up for the study of the borehole thermal reaming process in the granite block by means of angular plasmatron: 1- plasmatron; 2- granite block; 3- cooling system of the plasmatron.

The angular plasmatron operates as follows: plasmatron attached to the cable drops down into the borehole as well as cooling water supplies cooling channels 3 of the plasmatron, after that plasma forming gas supplies system of the channels 7. Then electric power source switches on that causes anode assembly 1 and cathode assembly 2 are subjected to the no-load voltage. After the plasmatron starts up plasma forming gas that supplies annular channel 6 into the arc zone transforms into plasma and through the plasma forming channels 4 as well as the plasma jets forming channels 5 flows out from the channels 5 as the swirling plasma jets influencing on the borehole surface.

In experimental study vertical axes of the plasmatron 1 as well as inlet orifice of the borehole in the granite block 2 were matched. After the granite spallation spalls were moving straight through to the tin pipe 3, into the box 4 by means of plasma flow (Fig. 2).

After the switching off the plasmatron blowing of the air through the tin pipe was performed. Then weighting of the spalls was carried out (Fig. 3) by means of VT-200 analytical balance. Accuracy class 4. Measurement accuracy ±10 mg.

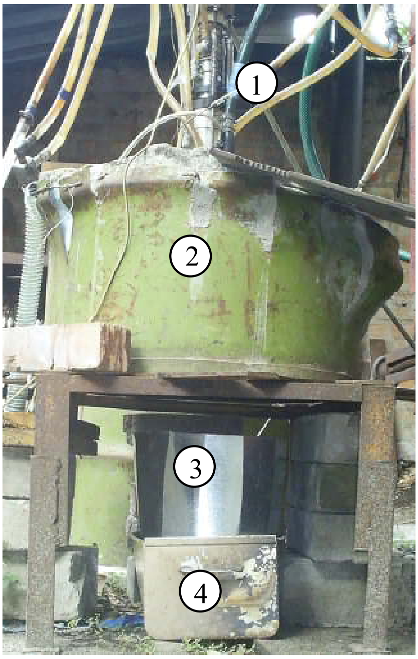

Fig. 2. Devices for the transportation of spalls to the box: 1- plasmatron; 2- granite block; 3- tin pipe for spalls transportation; 4- box for spalls accumulation.

Fig. 3. Spalls of rock after the thermal reaming of the borehole by means of the angular plasmatron.

Initial temperature of the granite block was within 18-20 °C. Initial diameter of the borehole was 105 mm. Borehole depth was 300 mm.

Main feature of the experimental study is determination of weight of the spalls for the calculation of the energy efficiency of the spallation process.

The values of parameters for the experimental study of the borehole thermal reaming by means of the angular plasmatron are shown in the Table 7.

Table 7. Parameters of the experimental study of the thermal reaming of the borehole by means of the angular plasmatron.

Parameter	Experiment						
	#1	#2	#3	#4	#5	#6	#7
Operating time of the plasmatron τ, s	12	22	23	24	26	29	35
Plasmatron power, kW	57.6	52.5	50.0	54.6	50.0	57.75	57.0
Energy of the plasma per experiment, kJ	691.2	1211.5	1194.7	1310.4	1406.8	1674.8	1995
Spalls weight, kg	0.007	0.013	0.0131	0.016	0.0143	0.028	0.028
Energy efficiency of the thermal reaming process *e*, kJ/g	98.7	93.2	91.2	81.9	98.4	59.7	71.2
Productivity of the thermal reaming process, g/s	0.583	0.560	0.569	0.667	0.511	0.967	0.801

The geometrical parameters of the borehole and the nozzles of the angular plasmatron are adopted in accordance with geometrical similarity to the technological and processing parameters of the plasmatron and diameter of boreholes before the beginning of the thermal reaming process.

3 Results and discussion

In Figure 4 comparison of energy efficiency of the thermal reaming process of the borehole of proper and other experimental research is shown [29].

Analysis of Figure 4 allows to make a conclusions as follows:

- increasing of the plasmatron operation time, i.e. duration of the thermal reaming process, leads to the prompt decreasing of the energy efficiency of the process; in particular, reaching of the thermal efficiency range of 0.97-4.48 MJ/kg, that was mentioned in the reference [29], possible for process duration that exceeds 55 s, namely from 55 s up to 70 s for plasmatron thermal power within the range 52.0-57.75 kW, that is quite comparable with experimental study [29], where for plasmatron thermal power of 100 kW energy efficiency of the thermal reaming process reaches the range 0.97-4.48 MJ/kg while process duration is 100 s.

Thus, time range for spallation energy efficiency within the range 0.97-4.48 MJ/kg for hardness coefficient range of f=8-12 and plasma thermal power 52-57.75 kW is obtained.

In the Table 8 comparison of the parameters of the borehole thermal reaming by means of the axial and angular plasmatrons is shown.

Table 8 shows that for equal values of the plasma thermal values as well as the energy efficiency of the spallation process application of the angular plasmatron allows to decrease spallation time that, in turn, leads to the increasing of the thermal reaming productivity.

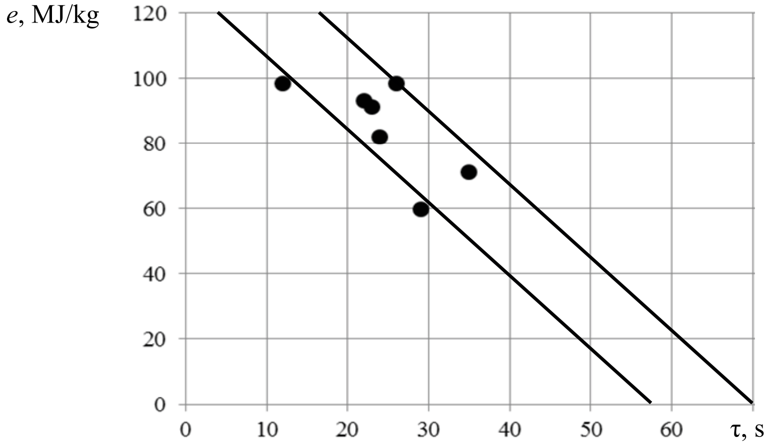

Fig. 4. Influence of the duration of the borehole surface heating on the energy efficiency of the thermal reaming by means of the angular plasmatron.

Table 8. Comparison of the parameters of the borehole thermal reaming by means of the axial and angular plasmatrons.

Plasmatron type	Parameters		
	Plasma thermal power, kW	Energy efficiency of the thermal reaming process *e*, MJ/kg	Time range for spallation energy efficiency reaching τ, s
Axial	52.2-57.3	0.97-4.48	90-170
Angular	52.0-57.75	0.97-4.48	55-70

Conclusions

Time range for spallation energy efficiency within the range 0.97-4.48 MJ/kg for hardness coefficient range of *f*=8-12 and plasma thermal power 52.0-57.75 kW is obtained.

For equal values of the plasma thermal values as well as the energy efficiency of the spallation process application of the angular plasmatron allows to decrease spallation time that, in turn, leads to the increasing of the thermal reaming productivity.

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