The feasibility evaluation of using cyclic thermal effect in the rock-cutting tools during drilling hard rock

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Abstract. The possibility of using cyclic thermal effect in drilling tools for softening of rocks is considered in the article. It is shown that during drilling in the phase of heating, the rock sections can actually be heated to 1000 °C, and it is possible to achieve even higher temperatures with the use of corresponding frictional heating elements. It has been found that the phase of cooling of the heated section of the rock can ensure guaranteed cracking of the rock for subsequent mechanical destruction.

Introduction

It is known that rapid cooling of heated rocks (thermal cycling effect) is an effective softening factor. It would be tempting to use this fact in real technological processes of rock destruction. If we are talking about drilling technologies, then in the drilling tool itself, in the process of its work, great energy is concentrated due to the axial force on the tool and torque. Most of this energy is spent on heat in the cutting zone, and a smaller part goes directly to the destruction process itself. Heat is redistributed between the tool and the rock, and then neutralized with flushing fluid or air (if drilling is performed with a blow). In other words, in a drilling tool there is everything for the realization of a thermal cycling effect - heat from the friction of the tool on the rock and cooling with flushing fluid. The question is whether it is possible to embed thermocyclic effect in specific tools and how effective will it work in terms of softening the rocks?

To answer this question, it is necessary to solve three interrelated tasks:

1) to determine the nature of rock behavior under thermal cycling effect;
2) to study the effect of various modes of rapid cooling on the strength properties of rocks;
3) to find out whether it is possible to effectively integrate the thermocyclic effect into specific rock cutting tools.

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Materials and Methodology

The system approach is used in the work to solve the stated problems, which includes the analysis and generalization of scientific and technical achievements and literary sources, combines theoretical and experimental research. The theoretical studies are based on analytical methods of the thermoelasticity theory, the rock fracturing theory, and the theory of heat conduction. The experimental studies include laboratory experiments to study the change in strength of strong rocks subjected to thermal cyclic interaction. The various rocks were considered: granite, quartzite, sandstone, marble, etc.

Results and Discussion

As a result of the recent studies, there is a general understanding of what happens in rocks with rapid cooling [1]. When the coolant gets on the heated surface of the rock, the cooled layer shrinks and tensile stresses develop in it, which, under certain conditions, "tear" the surface of the rock by macrocracks with the honeycomb structure that go deep into the body. Such cracking naturally affects the strength properties of rocks.

Therefore, if we talk about the use of thermocyclic effects in the tool, then before mechanical destruction it is necessary to have a section of the rock, first to be heated up to high temperatures (preferably 600 °C and higher), and then be cooled rapidly.

In the process of work, the tool rotates at fairly high speed. Taking into account the limited space in the instrument, the question arises: can we heat up a piece of the rock to high temperatures in a short period of time and cool it so that cracks begin to grow to a predetermined depth and sufficiently high density? The issues of heating and cooling require separate detailed study.

Heating a section of rock can be carried out by friction between the rock and any unit (stamp) embedded in the tool. When a unit slides over the rock, the heat flow goes into the body in two ways: the contact of the hot stamp with the rock and heat generated during friction. The temperature of the heating unit is determined by its geometrical parameters, sliding speed over the rock, the coefficient of friction of the rock-unit pair, the cooling mode of the unit and the force of pressing it against the rock. An important factor is also the coefficient of heat flow distribution between the rock and the tool.

The purpose of the stamp work is to heat the rock to high temperatures.

Studies carried out on diamond crowns 76 mm in diameter with standard drilling conditions using the method of cutting thermocouples embedded in the rock (granite) showed that under the crown sector the rock surface can be heated to temperatures above 1000 °C [2]. Thus, even without any additional friction elements in a tool, the rock can heat up to very high temperatures.

The purpose of the subsequent cooling cycle is to grow in the rock a system of macrocracks with a predetermined depth and an acceptable density.

An indirect confirmation of a possible significant change in strength of rock exposed to rapid cooling can be studies of changes in the velocity of longitudinal waves propagation and changes in gas permeability in samples subjected to thermal cycling [13].

The speed of the longitudinal wave propagation in the rods made of quartzite of the Kursk magnetic anomaly (10×10×140 mm) after heating to temperatures of 780 K for 20 minutes and cooling at room temperature after 15 treatment cycles decreases by 2 times.

Similar studies were conducted on samples of marble and other types of rocks and ores. The regular decrease in the velocity of propagation of elastic waves and its major changes after 1-2 cycles is usually associated with the formation of visible cracks - with a more subtle restructuring of the sample microstructure.

It also shows that the gas permeability of rocks after thermal cycling increases sharply, which confirms the conclusion that a developed system of cracks is formed in the rock.

It is known that in the heating phase, rocks experience compressive stress, and in the cooling phase, they experience tensile stress [3]. Since the resistance of rocks to stretching is much lower than that of compression, it is obvious that the main contribution to the violation of the integrity of the rock is played by the phase of rapid cooling.

It should be noted that even such “soft” thermocycling leads to such significant changes in the structure of the rock. With full confidence, we can expect that “hard” thermal shock regimes with heating temperature exceeding 780 K and water cooling cause more significant violations of micro- and macro-fracturing of rocks.

In the Ukrainian State University of Chemical Technology the experiments were conducted to directly confirm the nature and ability of influencing to the strength characteristics of rocks by thermal cycling effects. The study was conducted to study the changes in the compressive strength using a single thermal cycling treatment with different heating-cooling cycles for glass and granite.

Glass was used as a material that simulates rock. In terms of its physical and mechanical properties, it is close to rocks and the system of cracks after thermal cycling is very clearly seen in it. In addition, the effect of different quenching modes on the change in impact toughness of granite samples was studied.

To measure the compressive strength, the K-108 glass samples of 30×30×35 mm size and 10×10×10 mm granite size were prepared. To study the impact toughness of granite, prismatic samples with a size of 10×10×10 mm were manufactured. When studying strength with different values of temperature difference $\Delta T = T_h - T_c$ between heating and rapid cooling, all samples were slowly heated for 60 minutes in a muffle furnace to a predetermined temperature T_h, and then cooled rapidly by dipping in water at a temperature T_c =10-20 °C.

Compressive strength was determined on a tensile testing machine R-10 throught the compression of the samples until the moment of destruction. To obtain the value of one point, 4-5 samples were taken. Impact toughness, showing the energy intensity of the destruction by impact, was determined on a pendulum scraper MK-30A. To obtain the values of one point with specified ΔT at least 3 samples were broken.

The results of strength studies under various thermal cycling conditions are shown in Table 1.

The glass was tested when heated to a temperature of 400 °C, as with more heating the glass begins to lose elasticity. Granite was heated to a temperature of 800 °C.

The compression test shows that all samples retain a sufficiently high load capacity even if they are broken by a dense network of cracks (this is especially evident on glass samples).

The levels of fracture energyof granite samples depending on the conditions of the heating-cooling cycle are given in Table 2.

The compressive strength of glass in one cycle of heating-cooling with a temperature difference $\Delta T = 400$ °C decreases 1.7 times, coal – 2 times. The strength of granite at a temperature $\Delta T = 400$ °C decreases 1.1 times and 2 times at $\Delta T = 800$ °C.

Thermal cycling processing has the greatest influence on impact destruction performance. Thus, the fracture energy of granite samples during thermal cycling processing $\Delta T = 400$ °C decreases to 1.22 times, and already 3.4 times for $\Delta T = 800$ °C.

The greatest reducing in the strength of granite during thermal cycling begins with heating of more than 500 °C. Perhaps this is due to phase transitions in the quartz mineral, which is part of granite.

Let's consider the conditions necessary for the formation and development of cooling cracks. This issue was raised in [1-6]. In all cases, solving the problem of the destruction onset when the temperature dropped to the surface, it was assumed that the rocks contain a network of microcracks distributed in volume with a certain density [7].

Table 1. The influence of thermal cycling on the strength of glass and rocks.

Material	Temperature difference heating cooling ΔT, °C	Strength according to the method of crushing, f_{crus}	Compressive strength, MPa
Glass	No processing	1.95	201.3
	100	1.81	135.6
	200	1.78	135.2
	300	1.66	120.0
	400	1.58	118.0
Granite	No processing	9	204.3
	100	9	203.7
	200	9	203.0
	300	9	202.1
	400	8.2	190.2
	500	7.5	181.2
	600	5.3	153.7
	700	5.1	110.3
	800	4.9	100.7

Table 2. The fracture energy of granite samples on the scraper.

Temperature difference ΔT, °C	The fracture energy of samples
No processing	0.208
100	0.200
200	0.194
300	0.191
400	0.172
500	0.153
600	0.072
700	0.067
800	0.061

Part of these natural microcracks goes to the free surface of the rock. In addition to the natural cracks in the rock, the artificial fractures formed on the surface by rock-destroying tools (pre-fracture zone) are added [8]. The substance of the issue is, as a result of a sharp decrease in temperature on the surface of the rock (thermal shock), in the cooled layer the powerful tensile stresses develop, which cause the growth of microcracks located in this layer. In all cases [1, 3, 4, 6], the problem was solved for the most severe cooling conditions (boundary conditions of the first kind). Analysis of the results of the decision shows:

a) cooling cracks do not develop in the rock immediately, since the start of cooling, but after a certain period of time, called the delay time $\tau_{\min}$;

b) the delay time decreases with increasing temperature difference ΔT between the temperature of the heated rock T_h and the temperature of the cooling liquid T_c:

$$\Delta T = T_h - T_c \tag{1}$$

c) cracks develop into a rock with a slowdown asymptotically approaching to a certain value;

d) the rate of cracks growth may exceed the rate of thickness growth of the cooling zone, in other words, the cracks may extend beyond the boundaries of the cooled layer;

e) there is a group of microcracks in the rock, which under no circumstances develop at a given ΔT.

The delay time of destruction is determined by the formula [1]:

$$\tau_{\min} = \frac{729 \cdot K^4}{\pi^7 \cdot a \cdot \sigma_*^4} \tag{2}$$

where K - rock adhesion modulus (material constant) [7], N/m$^{3/2}$; a - thermal diffusivity of the rock, m^2/s; σ_* - ultimate stress at the boundary of a half-space when the temperature drops from T_h to T_c, N/m^2:

$$\sigma_* = \sigma_{\max} = \frac{\beta \cdot E \cdot (T_h - T_c)}{1 - \mu} \tag{3}$$

β - coefficient of linear thermal expansion of the rock, K^{-1}; E - Young's modulus of the rock, N/m^2; μ - Poisson ratio of the rock.

The Barenblatt destruction criterion was used in solving this problem. This criterion establishes the relationship between the material constant K, surface energy density γ, Young's modulus E, and Poisson's ratio μ by the following relations [9]:

- for flat deformation

$$K^2 = \frac{\pi \cdot E \cdot \gamma}{1 - \mu} \tag{4}$$

- for flat stress state

$$K^2 = \pi \cdot E \cdot \gamma \tag{5}$$

The rate of cooling crack development into the rock body is determined by the dependence:

$$V = F(k) \cdot a \cdot \left(\frac{\sigma_*}{K}\right)^2 \tag{6}$$

where $F(k)$ - function, depends on the ratio $K = \frac{l}{l_*}$; l - the length of the growing crack at a given time, mm; l_* - the minimum crack length disclosed by the stress σ_*, mm; is determined from the well-known Griffith dependence for an infinite plate with a rectilinear crack, stretched by external stresses σ_*, directed perpendicular to the crack orientation line [10]:

$$\sigma_* = \frac{K \cdot \sqrt{2}}{\pi \cdot \sqrt{l_*}} \tag{7}$$

The relationship between cooling time τ and the length of a growing crack is expressed by the formula:

$$\tau = \frac{4 \cdot l^2}{\pi^3 \cdot a \cdot \left(\sqrt{\frac{l_*}{l}} - 1 \right)^2} \tag{8}$$

The nature of the dependence $\tau(l)$ is shown in Figure 1.

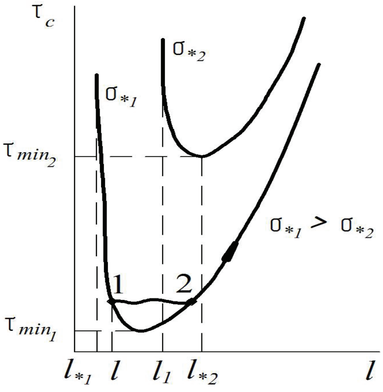

Fig. 1. The nature of the crack development during cooling of the rock surface.

Analysis of dependence (8) and Figure1 shows that if a crack in a rock is very small, then to begin the development of a crack, an action of stress close to the maximum is required over almost its entire length. This requires a delay time, which is greater, the smaller the length of the crack in the body is, and goes to infinity when the length of the crack in the rock is equal to l_*.

On the one hand, as the length of the crack in the body increases, the delay time decreases. This is due to the fact that achieving a mobile - equilibrium state does not require such intense loading along the entire length of the crack, and stress value closer to its contour may be noticeably less than the maximum. On the other hand, it increases, since less strength corresponds to a longer initial crack length. The conjunction of these two events just leads to the fact that the curve $\tau(l)$ passes through a minimum. For large lengths of cracks in the rock, the mobile - equilibrium state in their tops is reached when tensile stresses are concentrated in a relatively narrow layer and their effect on the crack is reduced to the action of a concentrated force, which, as is known, causes a steady development of the crack (right branch of the curve in Figure 1). After the crack begins to spread under the action of increasing concentrated force, a relatively slow expansion of the layer occurs. In this layer, tensile stresses act similar to the action of a concentrated force.

From the sense of l_{*1}, it follows that a crack of length $l< l_{*1}$ will not develop. If the crack has a length $l>l_{*1}$, then the nature of its further development is determined by comparison with the value of $l_\tau = l_1$ (Fig. 1). If $l< l_1$, then after an appropriate delay time $\tau = \tau_1$ the crack develops dynamically, moves from position 1 to position 2, and then grows steadily. If $l>l_1$, then after an appropriate delay time, the crack develops steadily right away.

Experimental observations of patterns of cooling cracks development in the samples of granite, jespilite, Shokshinsky quartzite, glass showed that with thermal shock, the surface of rocks is covered with a grid of cracks growing inwards the samples as they cool further. The depth of cracks penetration inwards the body with a sufficient degree of accuracy can be determined by the dependence (8). If the rock is later subjected to mechanical destruction, then the parameters of mechanical destruction will depend not only on the depth of cracks penetration inwards the body, but also on their density in the rock.

Looking at the events occurring at the bottomhole during thermal cycling, it is necessary to take into account the possibility of phase transitions in rock minerals that occur during sharp temperature fluctuations on the surface [4]. Currently, there are about 400 minerals that are inherent in the phenomenon of polymorphism. The most studied mineral in terms of polymorphic transformations is quartz, which is one of a huge number of strong rocks.

When β - quartz (the main low - temperature modification) is heated to a temperature of 573 °C, it turns into α - quartz. The transformation of a low-temperature quartz into a high-temperature quartz is a process that proceeds without breaking coordination bonds; therefore, it belongs to the type of instantaneous transformations. When this mineral is cooled below 573 °C, α - quartz usually returns back to β - quartz. It was found [14] that with a sharp cooling of quartz heated above 573 °C, a specific shape of inversion cracks of the honeycomb structure is observed in it, which can be seen under a microscope. Cell cracks produced by quenching quartz from the overinversion region to the preinversion region are a diagnostic feature of α ↔ β quartz transformation [14]. Moreover, these transition cracks are formed only with intensive cooling (for example, with water) and they are not seen with slow cooling (for example, in the air). The degree of quartz cracking is very high. Thus, in experiments [14], a grid of cracks measuring $0.15\times(0.2\text{-}0.4)\ \text{mm}^2$ was obtained. If we take into account that during the formation of a complete honeycomb fracture structure, the development of cracks occurs both on the rock surface and inwards, then it is obvious that the depth of development of these cracks reaches, respectively, 0.15-0.4 mm. Such a structure of cracks can have a significant impact, for example, on the drilling process.

It should be noted that silica polymorphism has complex nature. During cooling of quartz, its volume decreases as follows [4]: 600 → 500 °C by about 2 %; 500 → 400 °C – by 1.5 %; 400 → 300 °C – by 1 %. The overall decrease in volume of quartz during cooling from 600 to 300 °C is about 4.5-5 %, while the density changes from 2.5 for α-quartz to 2.65 for β-quartz. The hysteresis of the transformation temperatures during heating and cooling is 0.5 %. The transition of α - quartz to α - tridymite at a temperature of 870 °C can influence the drilling process. With sufficiently intensive cooling of α-trithymite below 163 °C, it turns into β - tridymite, and when passing through the temperature limit of 117 °C to γ - tridymite. All of these transitions occur in fractions of a second and are accompanied by abrupt changes in volume, leading to cracking of rocks.

The problem of the grid parameters (density) of the formed cracks was considered in [1].

Thus, the state of the rock during the thermal cycling action on the surface can be described as follows. In the heating phase, the rock is heated to a certain depth. In the heated layer along the surface, compressive normal stresses dominate. In the cooling phase, starting from the surface, the sign of the stress changes to the opposite and the rock undergoes tensile stresses reaching a certain maximum value σ_* according to (3). As it cools, the thickness of the stretched layer of rock grows. Some time later, defined earlier as the delay time $\tau_{\min}$, microcracks in the rock begin to grow and merging together. They form a developed system of cracks in the surface layer. Further cooling leads to the event that in the surface layer in the process of growth all smaller cracks are involved. The density of the developed cracks at the surface increases. At the same time, the development of cracks deep into the body of rock occurs at a certain speed, exceeding the speed of the cooled rock layer.

Thus, sufficiently intensive cooling causes the surface layer to a subcritical state, when tensile stresses are created in the layer but there is no cracking and supercritical, when these stresses cause the process of cracking in the layer. The time moment when one state replaces another (critical moment) corresponds to the delay time $\tau_{\min}$.

If thermocyclic effect is performed in combination with mechanical destruction (combined destruction) then intrusion of a mechanical tool into the rock can be carried out both in the subcritical mode (penetration into the stretched rock) and in the supercritical mode - intrusion into the cracked rock.

Studies of the hardness P_w of stretched rocks performed on a special stand, allowing the indenter to be pressed into the mechanically stretched surface layer showed that the hardness of the stretched rocks is less than the unloaded [1].

The change in pre-stretching from 0 to the limit value σ_p reduces rocks resistance to pressing of the stamp by 30-40 %, and this relationship is almost linear. Obviously, prestretching can have the same effect on cutting resistance of the rock.

Hence, if thermocyclic effect is an integral part of mechanical drilling, then the mechanical load can be applied to the rock both in the subcritical mode of weakening (to the stretched rock) and in the supercritical (to the cracked rock).

When considering a specific drilling mode, it is necessary to know the pre-cooling time τ_0 (the time from the start of cooling to the start of mechanical action) and the cooling parameters — the temperature difference between the cooling medium and the rock ΔT, the cooling intensity — the heat removal coefficient α. If $\tau_0<\tau_{\min}$, then there is a subcritical mode of operation of the working body. If $\tau_0>\tau_{\min}$, then the working body works in a supercritical mode, during which cracks appear in the rock body, the length of which can be calculated by the formula (8).

Relationships (2), (6), (8) characterize the development of cooling cracks in rocks. They were obtained for harsh cooling conditions with boundary conditions (BC) of the first kind. In real drilling cases we deal with heated rock that is washed with liquid refrigerant (convective heat exchange) with boundary conditions of the third kind. The boundary conditions of the first kind are a special case of the conditions of the third kind and BC of the first kind are transferred to the BC of the third kind, when the relative heat transfer coefficient is:

$$H=\frac{\alpha}{\lambda}\to\infty, \tag{9}$$

where α – heat transfer coefficient; λ – rock thermal conductivity.

Based on the value of the Bio criterion:

$$Bi=\frac{\alpha x}{\lambda}, \tag{10}$$

where x – current coordinate deep in the rock body, it is possible to simplify the boundary conditions.

If the value Bi is relatively large $Bi>50$, then it is possible to take the temperature of the body surface equal to the temperature of the medium, i.e. instead of the boundary conditions of the third kind, it is theoretically possible to consider a simpler condition of the first kind [11].

If $10\le Bi<50$, then it is also possible to replace the boundary conditions of the third kind with conditions of the first kind with the introduction of certain assumptions. If, $0.2 \leq Bi < 10$, then such a replacement is impossible.

In [12], it was shown that an increase in the heat transfer coefficient when cooled with water to the limits $\alpha > 10^4$ W/(m^2·K) in a calculation plan approximates boundary conditions type I to type III.

The literary source [2] shows that for diamond drill bits with a diameter of 59 and 76 mm, the flow rate of washing liquid from Q = 20 l/min to Q = 80 l/min gives in the lower hole the heat removal coefficient from α = 9850 W/(m^2·K) to α = 43800 W/(m^2·K). Therefore, dependences (2), (6), (8) are applicable when calculating the processes of thermocyclic effects in real tools.

Let us estimate whether it is possible to achieve the actual cracking of strong rocks in very short intervals of rapid cooling, based on the capabilities of real tools. In the tool, in order to obtain the maximum cracking effect, it is necessary to ensure that the cooling time is longer than the fracture delay time $\tau_{\min}$ calculated from (2). In work [1] values $\tau_{\min}$ for various rock formations are given for different values ΔT . With $\Delta T = 600\,°\mathrm{C}$ the delay time of destruction for sandstone $\tau_{\min}$= 0.059 s, quartzite $\tau_{\min}$= 0.002 s, granite $\tau_{\min}$= 0.05 s. The analysis shows that these times $\tau_{\min}$ is quite consistent with the real times of the passage of the washing intervals over certain areas of the rock when diamond drill bits work with diameters of 59 and 76 mm.

Conclusion

The performed work shows that thermal cycling softening of rocks can be successfully implemented in drilling tools with appropriate consideration the behavior of rocks with rapid cooling.

Even in regular drilling tools, it is possible to create conditions under which sections of rock in the heating phase are heated to 1000 °C. The additional heating elements attachment can raise the heating temperature of the rock significantly above 1000 °C without negative consequences for cutting elements.

The process of cooling phase with guaranteed cracking of rocks by high-density cracks can also be organized in a drilling tool.

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