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Transient Thermal Shock Analysis of Drilling with Liquid Nitrogen

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Abstract

Inspired by the effect of thermal shock on rock failure, an innovation concept of drilling with liquid nitrogen is presented to improve the drilling efficiency in hard and high temperature formation. The main objective of this paper is to investigate the effect of rapid thermal shock on surface mechanical propertied and analyses the feasibility through theoretical and experimental methods. Base on the calculation results, it indicated that the tensile stress only occurred close to the surface, while the interior region was under compressive stress. Time and heat transfer coefficient, which have threshold values, are the key parameters for surface crack growth. Then hardness test experiment was carried out and the results showed the subcritical crack growth did not occurred, but average reduction in hardness, maximum load and yield limit reached 13.18%, 13.00% and 15.74% respectively after being cooled by liquid nitrogen for 5 seconds. The conclusion drawn that drilling with liquid nitrogen is a promising technology, even if the thermal stress is not sufficient to form a crack on the surface of the rock alone, the transient thermal shock is also conducive to reduce the penetration resistance of the bits and improve the rate of penetration, especially in high temperature wells. The new innovation technology of liquid nitrogen assisted drilling shows great potential in improving geothermal drilling efficiency and subsequent research should continue.

Keywords

Transient Thermal Shock; Surface Crack; Liquid Nitrogen; Geothermal Drilling.

1. Introduction

The effect of thermal shock on rock's failure and deformation is important in many engineering applications such as radioactive waste disposal[1,2], freezing and thawing cycles of rock[3], underground resource development[4], geotechnical engineering[5], rock weathering[6], and so on.

In deep and ultra-deep petroleum and geothermal reservoir wells, low rate of penetration (ROP) and high rock broken resistance perplex the engineers for a long time. A series of promising and innovative drilling methods, such as hydrothermal spallation [7-9], laser [10-12], electrical plasma [13,14], have been proposed and studied to tackle the issues. The core perspectives of these innovation technologies are to use high temperature fluid and induced thermal shock to accelerate hard rock broken. However, these technologies have not yet been widely applied to field operation so far duo to the narrow wellbore space and low energy transfer efficiency. Therefore, traditional drilling with tricone bit or PDC bit remains the preferred choice in long term. Thus, efforts to deal with low ROP caused by hard rock and short bit life in traditional drilling become imperative. Inspired by the technology of reservoir stimulation with liquid nitrogen [15-17], full use of thermal stress caused by liquid nitrogen to assist the bit drilling seems to be reasonable and promising in enhancing drilling performance. What's more, compared with hydrothermal spallation, laser, and electrical plasma, drilling with liquid nitrogen is easier to achieve, just replace the traditional drilling fluid with liquid nitrogen. Liquid nitrogen assisted drilling also has many advantages, such as not polluting the environment, reduce the thermal damage of the drill bit, do not damage the reservoir, and so on.

However, before the application of this technology in field, the mechanism and law of drilling with low temperature fluid need to be addressed , the feasibility analysis needs to be carried out first. Several relevant researches about the low temperature fluid affect the rock mechanical properties have been published. Perkins [18] developed a numerical method to calculate thermoelastic stresses distribution when cool water was injected into a hot reservoir. He pointed out that the thermoelastic stresses could create substantial cracks in the cooled region. Dusseault[19], Kocabas[20] and Bellopede[21]also found that the thermal stress generated by temperature difference between cooled fluid and hot rock could create new cracks and promote the old cracks propagation. Enayatpour and Patzek[22,23]noted that differential thermal expansion and contraction of the rock grains would induce tensile stress and shear stress, when the reservoirs cooled by cold water. Cai[24-26]studied the effects of liquid nitrogen on the pore structure and mechanical properties of coal, sandstone and shale. The experiment results showed that the surface of the rock crushed rapidly under the action of liquid nitrogen and the strength of the rock decreased, indicating that the low temperature liquid nitrogen is beneficial to the crushing of rocks. Kim [27] investigated the effects of rapid cooling and rapid unloading on rock damage through measuring P and S wave velocity. The results indicated that crack growth or crack healing occurred in different rock types. The hypothesis is that overall crack healing is expected when the amount of crack healing exceed the crack growth. Li[28,29], Guo[30], Zhang and Gao[31,32]investigated the effect of the temperature gradient on rock failure analytically and experimentally in gas drilling. The micro-drilling experiments were carried out by heating the rock to different temperatures while the injected gas was at room temperature. But the effect of heat transfer time on drilling performance was not taken into consideration.

However, most above conclusions were established based on the assumption of steady-state heat transfer, which is quite different from the transient heat transfer between drilling fluid and rock during drilling. As the rock at the bottomhole is constantly being cut quickly, the cuttings are constantly being taken away by the drilling fluid, the interaction time between drilling fluid and new rock surface is extremely short, so that heat transfer process should be treated as a transient process. This study is to investigate the effect of transient cooling shock on mechanical properties of rock surface and analysis the feasibility of drilling with liquid nitrogen.

2. The Theoretical Model of Transient Thermal Shock

The thermal stress mainly generated by anisotropic thermal expansion and contraction of the interior and exterior parts. Under transient heat transfer, rapid cooling can result in large tensile stresses on the surface while rapid heating can result in large compressive stresses [27]. Therefore, it is necessary to have an insight into temperature and thermal stress distribution during transient cooling and then analysis the surface crack propagation caused by thermal stress

2.1 The Interaction Time of Rapid Cooling During Drilling

The interaction between fluid and rock during drilling with bits can be divided into two stages. In the first stage, heat exchange occurrs between the fluid and the bottomhole rock surface. The second stage, the cutter cut the cooled rock surface into cuttings, exposing new rock surface to cutter thus forms a cycle. Illustrated by the example of PDC bit, the cooling time is equal to the time taken by the bit to rotate the angle of the adjacent blade, showed as Equation 1, the action time is less than one second, which is not enough to reach the state of steady heat transfer.

$$\tau = \frac{60}{Nn} \tag{1}$$

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Where:

N= rotation speed of PDC bits, rpm.

n= number of blades.

τ= interaction time, s.

2.2 The Crack Propagation Model

The drilling fluid is circulated during drilling so that the process should be deemed as a forced convection heat transfer process. The bottomhole rock was assumed to be an infinite elastic strip. The equations for the transient forced convection heat transfer at the bottom are as follows:

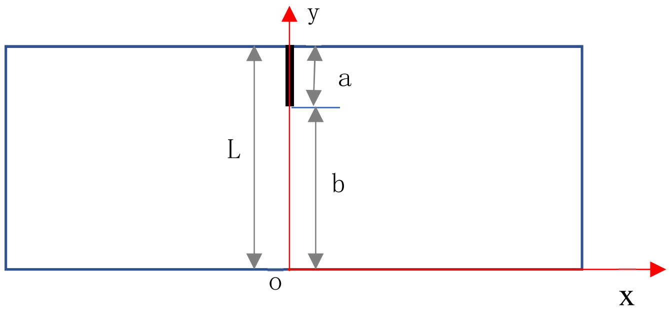

Figure 1. The configuration of an infinite elastic strip (L>>a)

$$\frac{t-t_\infty}{t_0-t_\infty}=erf\left(\frac{L-y}{2\sqrt{a\tau}}\right)+\exp\left(\frac{h(L-y)}{\lambda}+\frac{h^2a\tau}{\lambda^2}\right)erf\left(\frac{L-y}{2\sqrt{a\tau}}+\frac{h\sqrt{a\tau}}{\lambda}\right) \quad (2)$$

The temperature difference is:

$$\Delta t=t-t_0=T(y,\tau) \quad (3)$$

$$\alpha=\frac{\lambda}{\rho c} \quad (4)$$

Where:

α = thermal diffusivity, m2/s;

ρ= density, kg/m3;

λ= Thermal conductivity, W/(m·°C);

h= convective heat transfer coefficient, W/(m2·°C).

t=temperature of rock, °C.

t_∞= temperature of fluid, °C.

t0=initial temperature of rock, °C.

The thermal stress distribution can be calculated as [33]:

$$\sigma_{xx}{}^{T}(y,\tau)=\frac{\alpha E}{1-v}\left[-T(y,\tau)+\left(\frac{4L-6y}{L^2}\right)\int_0^L T(y,\tau)dy+\left(\frac{12y-6L}{L^3}\right)\int_0^L T(y,\tau)ydy\right] \quad (5)$$

The stress intensity factor of surface crack can be obtained from:

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$$K_I = 1.12\sigma\sqrt{\pi a} \tag{6}$$

Where KI is a mode I fracture toughness, σ is the tensile strength, a is the edge crack length.
The empirical equation of mode I fracture toughness and tensile strength was [27]:

$$\sigma_t = 9.35K_{Ic} - 2.53 \tag{7}$$

Where σ_t is the tensile strength of the rock.
Crack growth is a time-dependent behavior in brittle rock failure. Das & Scholz [34], Costin [35] point out that subcritical crack growth is one of the main causes of time-dependent behavior in brittle rocks. Though the stress intensity factor does not reach the fracture toughness, crack can also grow slowly. The subcritical mode I crack growth can be described as the power law version [36,37].

$$v = \frac{da}{dt} = A\left(\frac{K_I}{K_{IC}}\right)^n \tag{8}$$

Where:
v is the time-dependent crack velocity (m/sec),
da is the incremental crack length (meters),
dt is the incremental time (sec).
A and n are the subcritical crack growth parameters .Typical n and A values for rocks have been found to vary from 11-100 and 10-1-10-5 m/s respectively [27].

2.3 Case Study

Liquid nitrogen is a colorless, odorless and transparent liquid with low viscosity. In terms of chemical property, it is inert and free of synthetic substances. At normal temperature and pressure, it is liquid with extremely low temperature thereby it is often used as a highly efficient refrigerant. This kind of non-toxic, environment friendly and low-cost liquid, therefore, could be potential and excellent drilling fluid in high temperature petroleum wells and geothermal reservoir wells. In order to explore the feasibility of hard rock drilling with liquid nitrogen, hard purple sandstones from Shandong province were prepared. The mechanical parameters of rocks was gained by the triaxial compression experiment. The cohesion strength is 19.82MPa, internal friction angle is 47.43°, uniaxial compressive strength is 87.4MPa, and tensile strength is 5.7MPa. Young's modulus is 15.05GPa, Poisson's ratio is 0.287. The thermodynamic parameters are showed in Table 1.

Table 1. the thermodynamic parameters of calculation

Properties	Values	Unit
Rock density(ρ)	2.52×10^3	kg/m^3
Thermal conductivity(λ)	3.42	W/(m·°C)
Specific heat capacity(c)	0.82×10^3	J/(kg·°C)
Forced convective heat transfer coefficient of LN_2(h)[38]	300	$W/(m^2\cdot°C)$
Forced convective heat transfer coefficient of air(h)	20	$W/(m^2\cdot°C)$
coefficient of thermal expansion(α)	3.567	$10^{-6}/°C$
K_{IC}	0.88	MPa $m^{0.5}$

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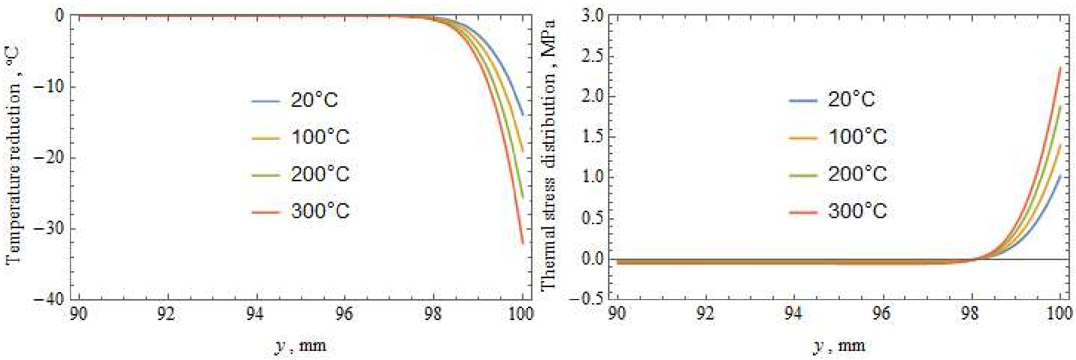
The rotation speed and blade number in the above equations are assumed at 54rpm and 4. In order to make sure that the heat cannot transfer to the bottom of the strip during the rapid cooling by liquid nitrogen, the thickness is set to 100mm, which is much larger than the crack length. The temperature difference distribution and thermal stress distribution were calculated, as shown in Figure 2. It is clear that the maximum temperature difference up to 496°C only lower the rock temperature by 30°C. Maximum tensile stress was about 2.3MPa, which is found on the rock surface. Figure 2(a) showed the temperature reduction distribution with depth. The curves illustrated that the depth affected by liquid nitrogen was limited, with about 2mm effective interaction distance during the transient cooling. Within the depth, the temperature drops rapidly. Figure 2(b) showed the thermal stress distribution versus depth. Tensile stress also generated within the effective interaction depth and a peak value appeared on the rock surface. During the rapid cooling, interior rocks out of interaction region were under constant temperature and subjected to weak compressive stress, which has been proved by Nied [33]. Therefore, in the process of rapid cooling, cracks were in a close-open competitive relationship.



(a) temperature reduction distribution (b) thermal stress distribution

Figure 2. the temperature reduction and thermal stress distribution

The stress intensity factor reflects the elastic stress field of the crack tip, which is an important physical parameter to judge the crack propagation. Figure 3 displayed the variation of stress intensity factor with time, crack length, heat transfer coefficient and initial rock temperature. The critical stress intnesity factor is 0.88MPa·√m, marked by the dotted line in the figures. As shown in Figure 3(a), the stress intensity factor increases rapidly and then decreases slowly with time, the peak of which appears after 30 seconds. Figure 3(b) shows that the crack tip is subjected to tensile stress with a positive stress intensity factor when the crack length is less than 6 mm while the crack tip is subjected to compressive stress with a negative stress intensity factor if the length exceeds 6mm. The stress intensity factor reaches its peak value when the crack length is 1.5 mm. The relationship between stress intensity factor and heat transfer coefficient was showed in figure 3(c). The stress intensity factor varies with the convective heat transfer coefficient at different initial temperature of rock. Higher convective heat transfer coefficient results in a larger stress intensity factor. When heat transfer coefficient increases from 0 to 3000, stress intensity factor increases dramatically. However, for a heat transfer coefficient exceeding 3000, the increase of corresponding stress intensity factor slows down dramatically. This maybe attributed to that at such high heat transfer coefficient, the temperature at the crack tip is very close to the liquid nitrogen thus the thermal stress remains stable and does not change with a higher coefficient. Figure 4(d) shows that the stress intensity factor increases linearly with the initial temperature of the rock.

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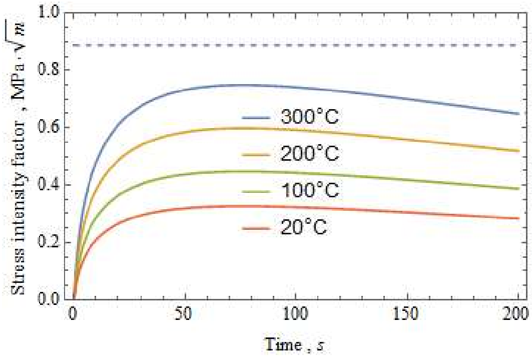
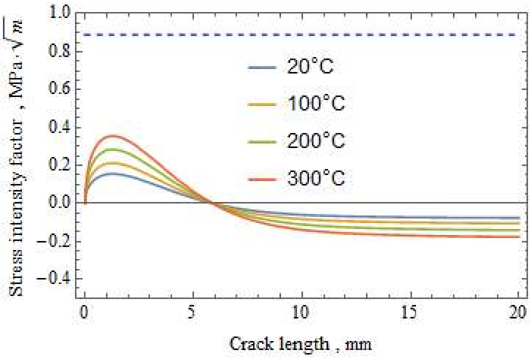
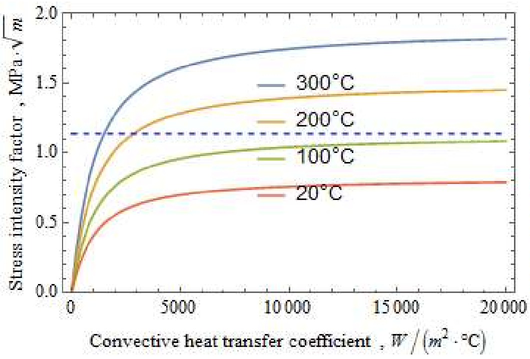


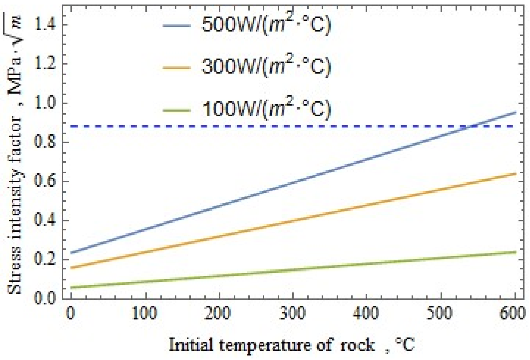
(a) a=1mm,h=300 W/(m2·°C)



(b) t=5s,h= 300W/(m2·°C)



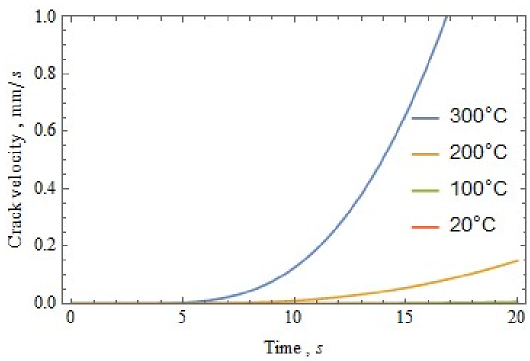
(c) a= 1mm, t=5s



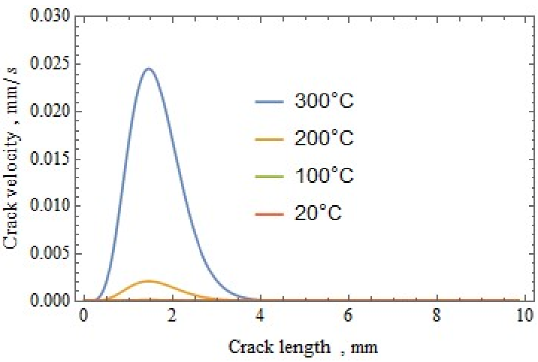
(d) a= 1mm, t=5s

Figure 3. Stress intensity factor versus time (a), crack length (b), heat transfer coefficient(c), initial temperature (d)

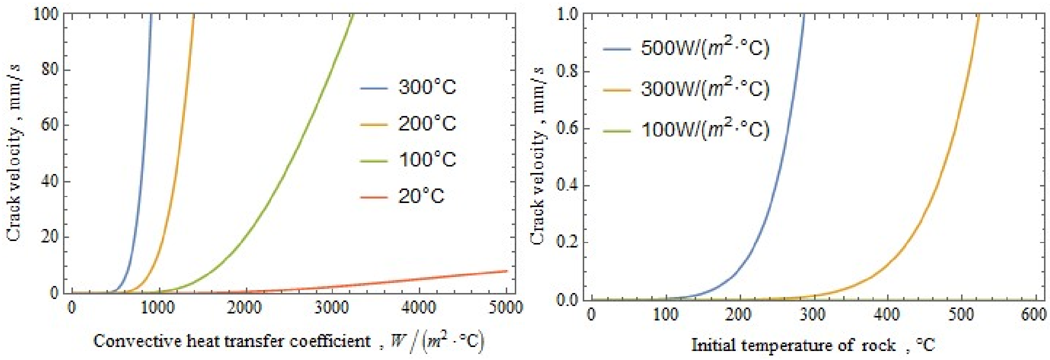
In order to determine wherther transient thermal shock is conducive to crack growth , stress intersity factor and crack velocity were calculated. Based on equation7, the fracture thougness is 0.88MPa·√m. Using favorable n and A values for crack growth (low n, high A), the surface crack length is 1mm, convective heat transfer coefficient is 300 W/(m2·°C). Figure 4 demonstrates that the initial temperature of the rock has a great effect on the velocity of crack propagation. When the rock temperature is 20 °C and 100 °C, the crack propagation rate is almost zero. The velocity of crack propagation increases exponentially with the initial temperature of the rock, which indicates that the efficiency of rapid cooling assisted drilling increases significantly with temperature of the bottomhole rock. As illuminated in figure 4(a) and 4(c), the interaction time and heat transfer coefficient are the key parameters for crack growth. It is noted that all of them have a threshold for a certain temperature. When this threshold is overcome, the crack velocity grows geometrically. As the rock used in this study is so hard (the hardness grade is 12) that cracks grow at only 0.01mm/s after 5 seconds when the initial temperature is 300°C. When the temperature is 20°C, the crack hardly expand in 20 seconds.



(a) a=1mm,h=300 W/(m2·°C)



(b) t=5s,h= 300W/(m2·°C)



(c) a=1mm,t=5s (d) a= 1mm, t=5s

Figure 4. the crack velocity versus time and convective heat transfer coeddicient

Therefore, in overall rock initial temperature range of 20 to 300°C, significant tensile stress is induced by rapid cooling of liquid nitrogen. Given that rock is a poor heat conductor, interaction, heat transfer coefficient and initial temperature are the key parameters for crack velocity and stress intensity factor. The encouraging conclusions is that improving the convective heat transfer coefficient and extending interaction time appropriately can enhance the stress intensity factor dramatically, which indicating a promising feasibility of drilling with low-temperature fluids, especially for wells having a higher temperature gradient.

3. The Validation By Experiment

As showed in the case study, stress intensity factor caused by thermal stress is lower than the critical value. The effectiveness of thermal stress for drilling needs to be validated. Because thermal stress only exist near the surface and effective interaction depth is limited, the traditional triaxial rock mechanics test fails to provide an accurate and authentic variation of surface properties. The hardness test is carried out by pressing a 2.15 mm metal cylinder into the rock to characterize hardness. The test mechanism, as showed in figure 5, which is similar to that of the cutter invading the rock. In this process, the stress distribution within the rock can be divided into three regions. Zone I is subjected to the tensile stress area, zoneII is the compressive stress region, and the zone III is the transition zone.

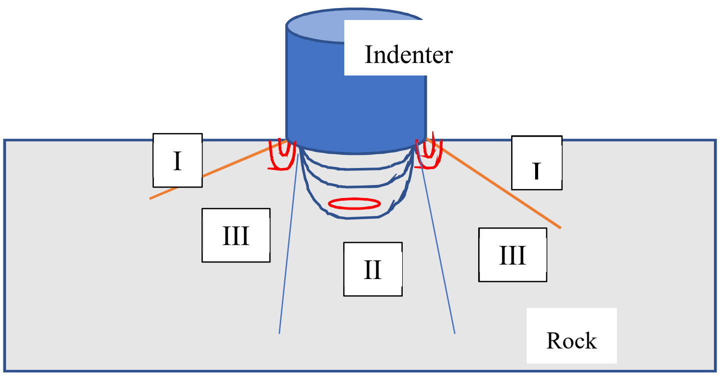


Figure 5. The stress distribution during hardness test

The rock sample is cut into a cub with side length of 20cm. The left side is sprayed with liquid nitrogen for 5 seconds while the right side is not treated, as showed in Figure 6(a). Then use the rock hardness tester to determine the hardness of both sides of the rock quickly, as showed in Figure 6(b). During the rapid liquid nitrogen cooling, significant tensile stress exist near the surface, so the thermal stress mainly affect Zone I.

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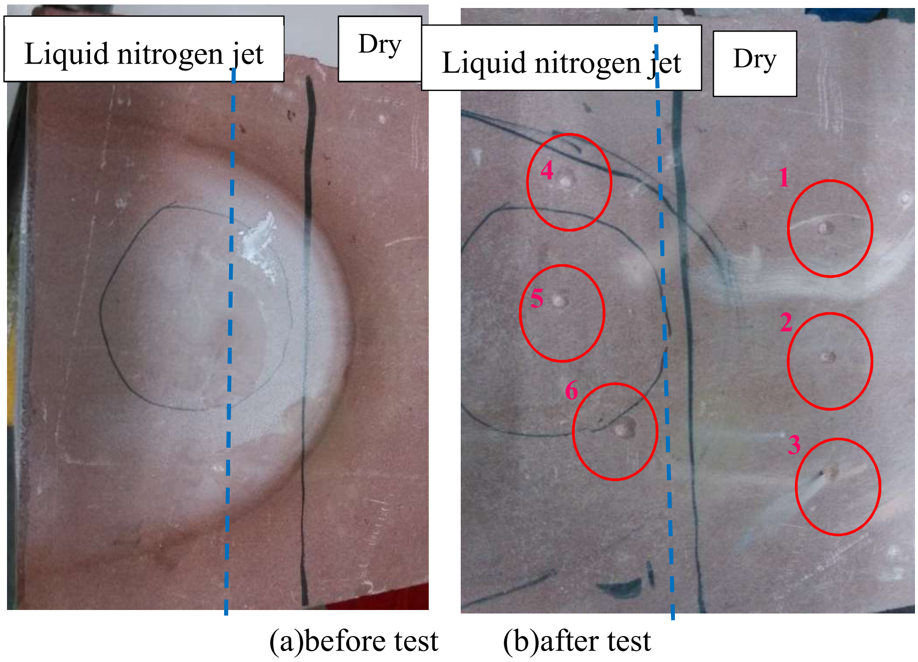

Figure 6. the samples used for hardness test

3.1 Analysis of the Experiment Results

Through the experiment results, it is observed that no crack formed on the surface with liquid nitrogen cooling, which proved that the thermal stress alone was not enough to break the rock when the initial temperature is 20°C and interaction times is 5 seconds. The curves of penetration force versus depth are displayed in Figure 7. Curve 1, Curve 2 and Curve 3 display the hardness test results for rocks that are not treated with liquid nitrogen respectively. Curve 4, Curve 5 and Curve 6 show the test result of rocks with rapid cooling. Though the tendency of curves is similar, the maximum force for invading into rapid cooled rock (solid line) diminished compared to that of the original rock (dotted line), which means that the tensile stress caused by thermal stress near the surface reduce the penetration resistance of the cylinder.

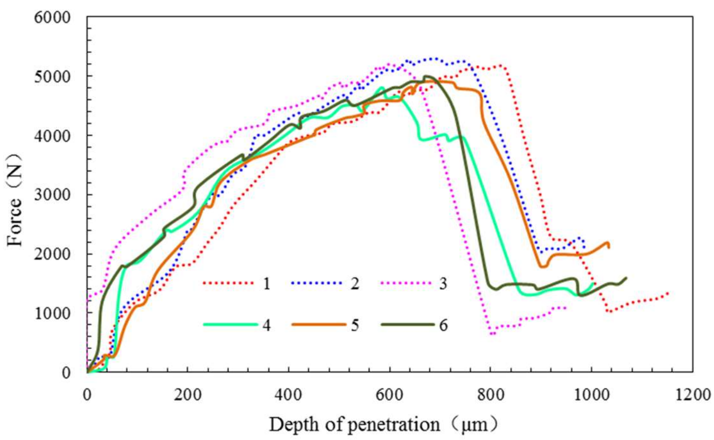

Figure 7. The curves of penetration force versus depth

The hardness, maximum load, yield limit reduction in hard sandstones under liquid nitrogen and dry conditions are determined by laboratory test. The average reduction in hardness, maximum load and yield limit are 13.18%, 13.00% and 15.74% respectively, the hardness grade and plasticity coefficient remains the same. Though stress intensity factor is lower than the critical value, the thermal stress could reduce the mechanical force for indenter invading the rock. Full use of this point can significantly reduce the penetration resistance of bit and improve the rate of penetration, thus significantly improving the efficiency of hard and high temperature rock drilling.

Comprehensive experimental results and theoretical analysis show that, though the thermal stress induced by thermal shock is not enough to form and promote cracks propagation on the rock surface, it makes significant contributions to reducing the resistance for bits penetration. Therefore, drilling with liquid nitrogen seems to be a promising technology in high temperature and hard formation. Besides, liquid nitrogen also can reduce the temperature of bit, which could prolong the life and reduce the frequency of bit trips.

4. Conclusion

According to the analysis, several conclusions, which may be important for drilling engineering in high temperature and hard formation, can be drawn from this paper.

(1) Tensile stress caused by transient thermal shock only exist near the surface and the interior of the sample is under weak compressive stresses.

(2) Interaction interval and heat transfer coefficient, which have threshold values, are the critical parameters of transient thermal shock generated during rapid cooling. When this threshold is overcome, the crack velocity grows geometrically as the parameters increase. Prolonging the interaction time and increasing the heat transfer coefficient would improve the performance dramatically when drilling with liquid nitrogen.

(3) Though the thermal stress is not sufficient to promote the surface crack propagation, it could reduce the hardness and yield limit of rock, which is beneficial for reducing the penetration resistance.

(4) As the thermal stress induced by thermal shock would make significant contributions to reducing the resistance for bits penetration, drilling with liquid nitrogen has a potential to increase the penetration rate and seems to be a promising technology in high temperature and hard formation drilling.

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