

Original Paper

Experimental research on failure mechanism and evolution characteristics of thermal-treated granites under action of impact load with PDC cutter



Hao-Yu Wang^a, Yan Xi^{a,b,c,*}, Wei Lian^d, Jun Li^{c,d}, Hai-Long Jiang^e, Yu-Mei Li^e

^a College of Architecture and Civil Engineering, Beijing University of Technology, Beijing, 100124, China

^b Chongqing Research Institute of Beijing University of Technology, Chongqing, 401121, China

^c State Key Laboratory of Petroleum Resources and Engineering, China University of Petroleum (Beijing), Beijing, 102249, China

^d Oil and Gas Engineering Institute, China University of Petroleum (Beijing) at Karamay, Karamay, 834000, Xinjiang, China

^e School of Automation, Beijing Information Science and Technology University, Beijing, 100096, China

ARTICLE INFO

Article history:

Received 3 September 2025

Received in revised form

22 December 2025

Accepted 21 May 2026

Available online 27 May 2026

Edited by Jia-Jia Fei

Keywords:

High temperature

Percussive drilling tools

Bit-SHPB test

Impact crater reconstruction

Rock-breaking efficiency

ABSTRACT

High rock temperatures and complex engineering environments are the most significant problems in enhancing the rate of penetration (ROP) and drilling tool efficiency for hot dry rocks (HDR). Studying the failure characteristics of different thermal-treated granites by PDC cutters during percussive drilling has profound significance in enhancing the compatibility between drilling teeth and rock during HDR mining and optimizing the drilling tool's efficiency in breaking rocks. Through drillability tests and SHPB tests, the present study explored the relationship between drillability and the dynamic behavior of granites. In addition, granites with different heating temperatures and cooling methods were subjected to dynamic rock-breaking tests by the SHPB system installed with the PDC cutter. Furthermore, the impact crater was quantified by 3D contour scanning technology, and the fractal theory was utilized to analyze the fragments. Then, the equations for the dynamic magnification factor of intrusion, fractal dimension, and specific rock-breaking energy of granite upon impact loading are discussed. According to the results, the impact crater size is closely associated with the heating temperature of the rock. Heating and rapid cooling treatments will affect the thermal shock damage and strength of rock, and then change the penetration depth, damage volume, and area of impact craters generated from the PDC cutter. The granite at 600 °C exhibits about 45% smaller fragment size than that at room temperature, while the damage degree of the liquid nitrogen-cooled specimen will be greater. According to the variation of dynamic magnification factor, fractal dimension, and specific rock-breaking energy of rock with thermal shock damage, it can be found that with the temperature increasing, the problems drilling tools need to solve gradually shift from increasing ROP to improving cleaning efficiency. The experimental results are expected to lay the ground for high compatibility between drilling tools and formation in HDR.

© 2026 The Authors. Publishing services by Elsevier B.V. on behalf of KeAi Communications Co. Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Hot dry rock (HDR), a clean, renewable, and safe resource, is the main direction of geothermal energy development (Brodsky and Lajoie, 2013; Yang et al., 2021). HDR usually refers to the high-

temperature rock mass (mainly granite and gneiss) without water or steam in the deep strata (3–10 km), whose temperature scope is primarily between 150 and 500 °C (Breede et al., 2013). At present, the development and utilization of HDR mainly involve the establishment of the Enhanced Geothermal System (EGS), which can realize the conversion of geothermal energy by bringing heat back to the ground surface through water injection after drilling (Qiu et al., 2024). Percussive drilling technology is widely used in EGS to ensure that production wells are accurately drilled into hydraulically fractured fractures (Song et al., 2023). During percussive drilling operations, the dynamic load created by the

* Corresponding author.

E-mail address: xiyan@bjut.edu.cn (Y. Xi).

Peer review under the responsibility of China University of Petroleum (Beijing).

percussion tool, the cutting force from polycrystalline diamond compact (PDC) teeth, and the change in rock mechanical properties under heating and cooling treatments all affect the rock-breaking performance of the drill bit (Xiao et al., 2022). Nonetheless, the destructive effects of drilling bits under varying environmental conditions have not been systematically and quantitatively assessed, resulting in poor compatibility between the formation and impact tools, which seriously affects the tool and bit life (Yang et al., 2024). Hence, the research on failure characteristics of different thermal-treated granites by PDC cutters during percussive drilling has profound significance in enhancing the compatibility between drilling teeth and rock in the HDR mining process and optimizing the drilling tool's efficiency in rock breaking.

Great hardness, high abrasiveness, and poor drillability of rock in HDR are the main reasons that restrict the rate of penetration (ROP), along with the drilling expenditure reduction (Rossi et al., 2020). As the drilling depth increases, the rock temperature in HDR rises, and the corresponding drilling difficulty and cost increase (Niu et al., 2025). Therefore, low-temperature drilling fluids have begun to be widely used to assist drilling tools in breaking rocks to improve drilling efficiency (Xue et al., 2024). The previous studies on the effects of high temperature and rapid cooling on the physical (Wu et al., 2019a; Li et al., 2024) and mechanical (Fan et al., 2018; Shao et al., 2020; Li et al., 2025; Wang et al., 2025) behavior of granite mainly focus on changes of the rock itself, without considering the interplay between the PDC cutter and the rock, a key factor that enhances the rock-breaking performance.

Additionally, one effective way of enhancing the speed and performance of HDR drilling is to apply percussive drilling tools, which generate dynamic loads through the reciprocating motion of the hammer to assist in breaking rocks (Li et al., 2021). Under the dynamic loading, the PDC cutter impacts and cuts the rock, thereby achieving rock fragmentation. Based on the transmission of stress waves under dynamic loading and the rotational cutting effects of PDC cutters, extensive theoretical assessments and laboratory tests have been conducted in recent years (Xi et al., 2023b; Chen et al., 2021; Dai et al., 2023). Through a series of indices like the cutting force, rock failure mode, and mechanical specific energy (MSE), detailed studies on the destructive properties of rocks at room temperature have been conducted (Dai et al., 2021; Zhu et al., 2022; Xiong et al., 2023). The research on high temperature rock has gradually increased in recent years, but these related experiments (Song et al., 2024; Shi et al., 2025) or simulations (Zhu and Dan, 2019; Song et al., 2021) do not combine the impact load with the action of high temperature rock to discuss. In general, prior studies has not highlighted the influence of impact load on the rock-breaking process of drill teeth, and has not yet explored the drilling bit-rock efficiency in breaking high-temperature rock upon impact loading.

However, despite the thorough investigations into the association of cutting depth with fragmentation characteristics, prior studies primarily focused on rocks at room temperature rather than exploring the drilling bit-rock efficiency in breaking high-temperature rock upon impact loading.

Summarizing the extensive research above, improving the drilling efficiency of HDR faces multiple obstacles, which can be categorized under the following two dimensions: (1) Considering factors such as establishment of the relationship between PDC cutters and rock as well as thermal and cooling treatments of rocks are complex, the cost of designing experimental research is relatively high. (2) Quantitative assessment of failure pattern and fragment size of PDC teeth on the rock under different conditions requires advanced equipment to support. Thus, further exploration into the rock-breaking effect of PDC teeth on the high-temperature granite is necessary.

Through the drillability test and SHPB test, the present study explored the relationship between drillability and the dynamic behavior of granites, integrating experiments with engineering applications. In addition, dynamic rock-breaking tests on granites with different heating and cooling methods were performed by the SHPB system installed with the PDC cutter, and the results were compared. Furthermore, the impact craters were quantified by 3D contour scanning technology, and the fragments were analyzed according to the fractal theory. Then, the energy conversion and rock-breaking performance under different conditions were discussed. The experimental results are expectedly to lay the ground for high compatibility between formation and drilling tools in HDR.

2. Experimental setup

2.1. Specimen preparation

Fine-grained granite of natural outcrops in Yueyang, Hunan, China, was studied. As shown in Fig. 1, the entire rock block was cored into standard rock specimens, which were processed according to the recommended rock dynamics testing procedure to meet the stress uniformity hypothesis (Dai et al., 2010; Zhou et al., 2012). According to the specimen size for rock mechanics tests specified by the International Society for Rock Mechanics (ISRM), each granite specimen has a height and diameter of 25 and 50 mm, respectively. The two specimen ends were delicately ground, so the surface flatness was controlled within 0.05 mm.

As a plutonic magmatic rock, the difference in mineral content will further affect its mechanical and physical traits. Besides, the varying adaptability of different mineral components to temperature and the external environment also needs to be considered (Cowie and Walton, 2018). The mineral content of the rock was analyzed based on the X-ray diffraction (XRD) test. The results demonstrated that the mineral composition of granite is evenly distributed, as displayed in Fig. 2. The contents of quartz (28.2%) and K-feldspar (27.4%) predominate. Conversely, the clay minerals (4.9%) exhibit the lowest content.

2.2. Heating and cooling treatment

As a vital geothermal resource, the temperature of HDR can usually reach 150 to 500 °C (Wu et al., 2019b). Therefore, the study focuses on the mechanical behavior of thermal-treated granite in a 200–600 °C temperature range. Target temperatures of 200, 300, 400, 500, and 600 °C were designed every 100 °C, with the control room temperature being 25 °C. Fig. 3 shows granite's thermal and cooling treatments, in which the former is carried out in the heating furnace, and the latter in the container with different cooling mediums.

For every target temperature and cooling method, we prepared three specimens. To avoid thermal shock during rapid heating, the heating rate was set to 2.5 °C/min (Xi et al., 2024). Each specimen was heated to the corresponding target temperature for 180 min for a uniform internal temperature distribution (Yin et al., 2019). Subsequently, the specimens were taken out of the furnace for instant cooling using three techniques (water, liquid nitrogen (LN₂), and natural cooling). Water cooling and LN₂ cooling are carried out in the container. Water and liquid nitrogen were replenished in time so that the specimens were completely immersed during the cooling process. All conditions were considered identical except for the temperature and state of the three media. The cooling time is set to 60 min to ensure it is thoroughly cooled. Finally, all the specimens after cooling treatments were subjected to 24 h of drying in a 105 °C furnace to mitigate the influence of rock moisture content over the subsequent experiments.

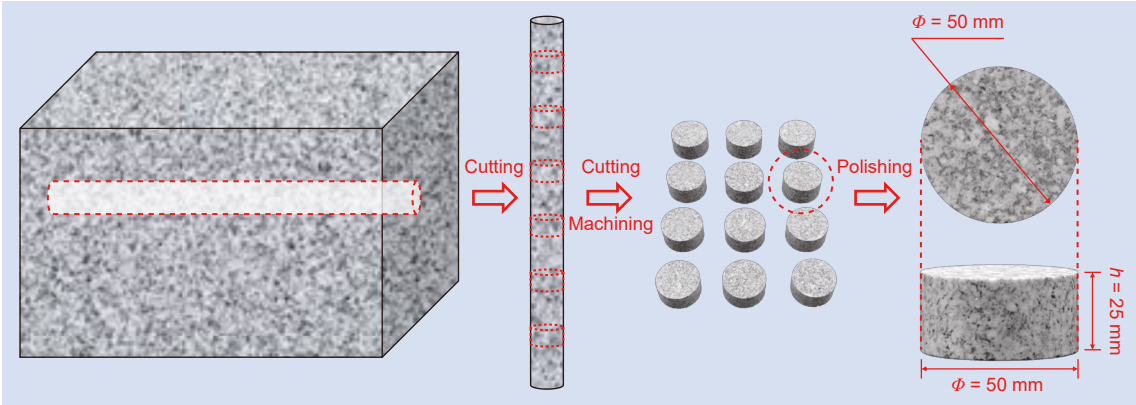


Fig. 1. The process of sampling and processing granite cores.

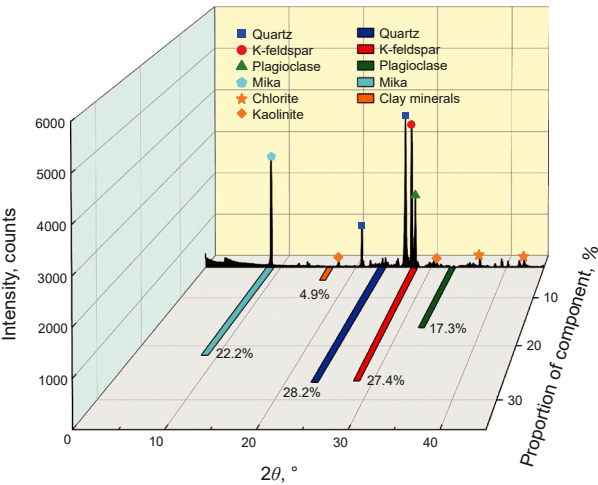


Fig. 2. XRD diffraction test results of the granite.

Fig. 4 shows the experimental design for studying the properties of thermal-treated granite and the interaction between the PDC cutter and high-temperature rock. In HDR drilling, the rock

must withstand high temperature and rapid cooling, and the joint influences of drill tooth cutting and impact loading (Dai et al., 2022). Therefore, the present work designed drillability and Split-Hopkinson Pressure Bar (SHPB) compression tests to determine granite's physical and mechanical behavior under different conditions. Then, the penetration characteristic, fragment traits, and energy consumption of granite were investigated through the Bit-SHPB test to improve the compatibility between high-temperature rock and drilling tools in HDR drilling.

2.3. Experimental process

2.3.1. Rock drillability test

In percussive drilling engineering, the rock-breaking efficiency is influenced by factors like formation lithology, formation environment, drilling parameters, and bit structure (Hu et al., 2021). Drillability usually acts as a measure for assessing the influence of intrinsic rock properties on the rock-breaking efficiency. Rock drillability value, which eliminates the effects of bit structure and drilling parameters on the rock-breaking efficiency in practical engineering, is a comprehensive index reflecting the drillability characteristics of rock specimens (Han et al., 2020; Huang et al., 2020). Therefore, drillability tests were conducted on thermal-treated granite specimens under different cooling treatments.

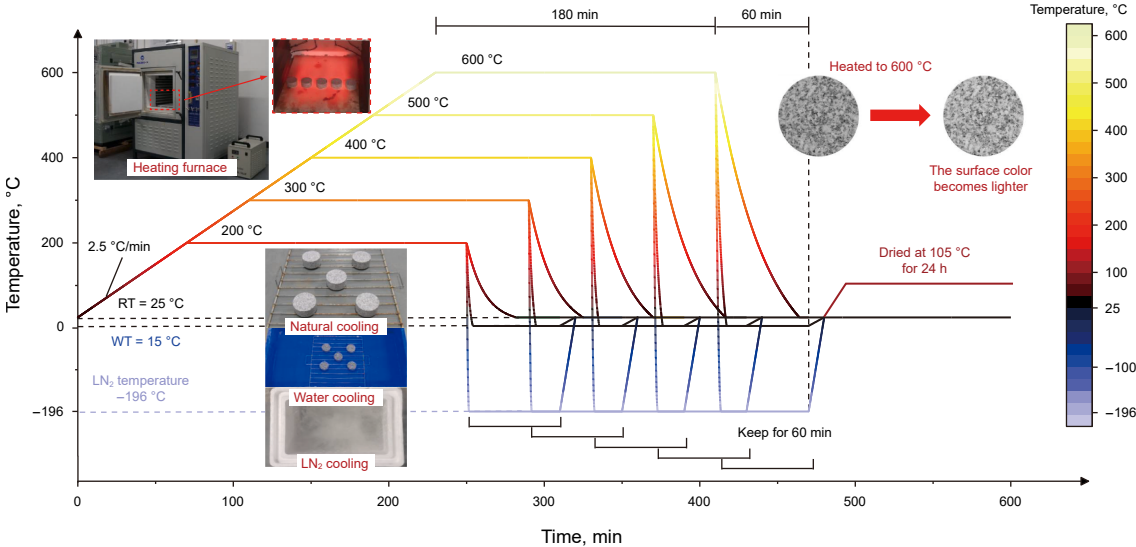


Fig. 3. Heating and cooling processes.

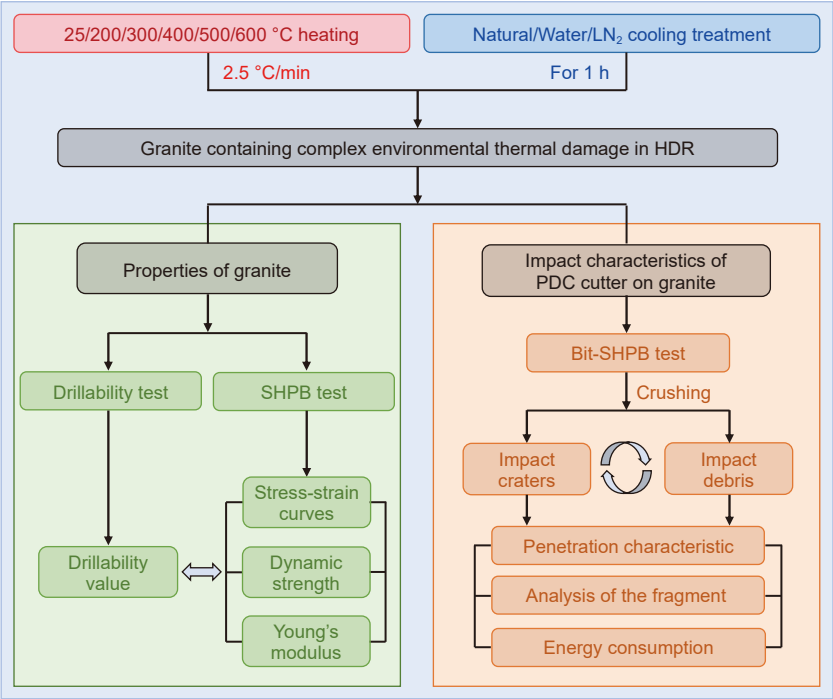


Fig. 4. Experimental design.

The test carried out by the drillability tester shown in Fig. 5 stringently follows the petroleum industry standards of *Rock Drillability Measurement and its Classification* (SYT5426–2016, 2016). The standard rock specimens fixed by the hand wheel and hand pump are tested on the equipment. Through rotational rock cutting by a PDC cutter under torque action and bit pressure, the times consumed for cutting an identical depth of 2.7 mm are recorded (Mao et al., 2018). The applied weight on bit (WOB) in the

drilling process was 500 ± 10 N, while the revolutions per minute (RPM) was 55 ± 1 r/min.

2.3.2. SHPB test and PDC cutter system

A dynamic compression test is conducted with the SHPB apparatus, comprising a gas gun, spindle-shaped striker bar, speed sensor, incident bar, transmission bar, and absorbing bar, as displayed in Fig. 6(a). Each bar and rock specimen is 50 mm in

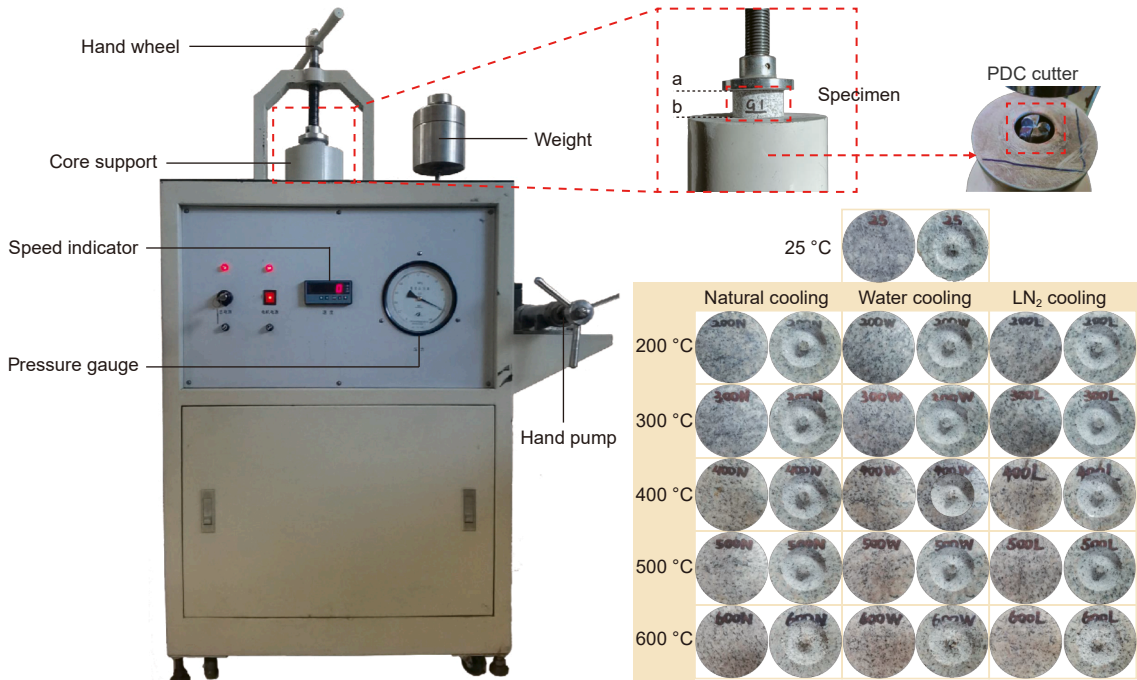
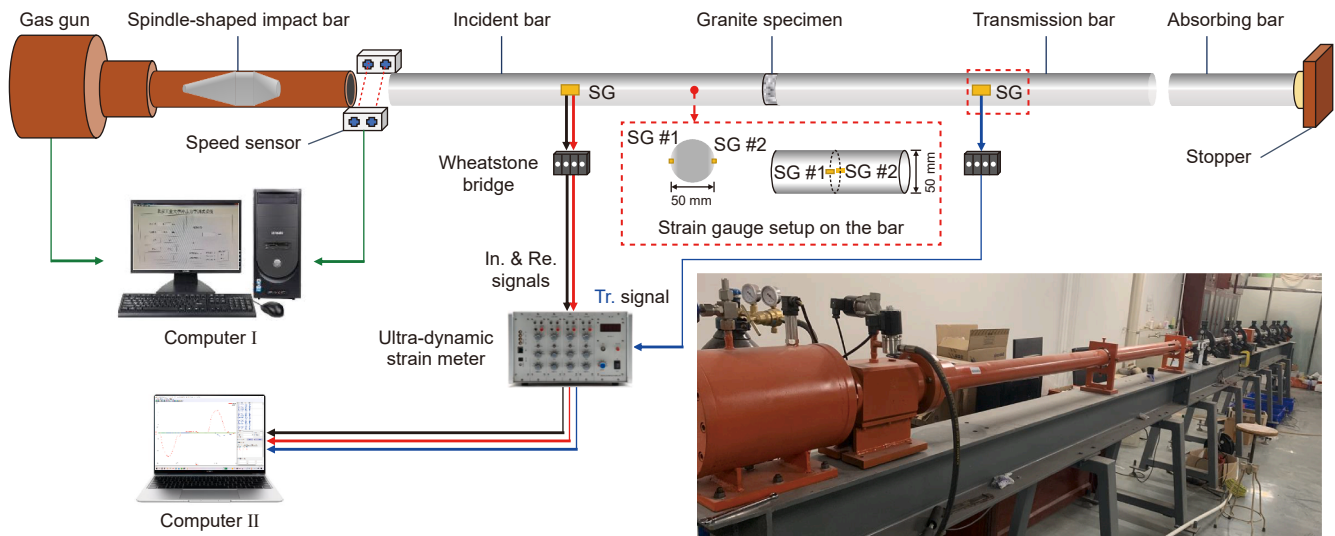


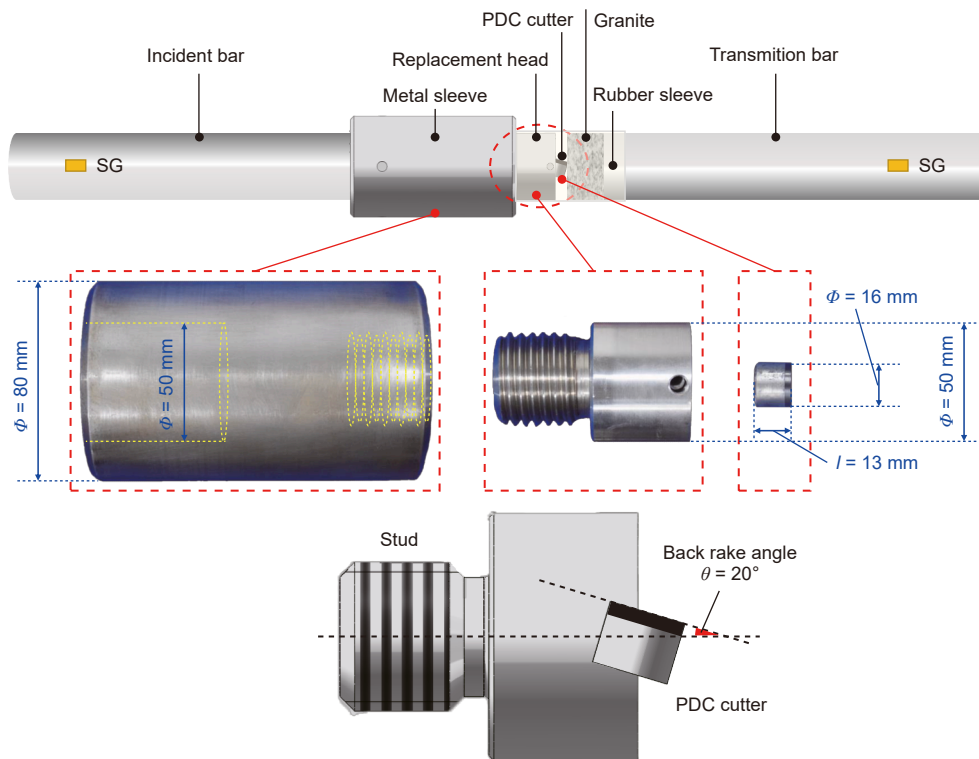
Fig. 5. Rock drillability testing equipment.

diameter. The striker, incident, and transmission bars are all made of high-strength alloy steel with a density of 7850 kg/m^3 and a Young's modulus of 210 GPa. The lengths of the 3 bars are separately 400, 2500, and 2500 mm. During the test, the free end of the incident bar is impacted with the striker bar to produce a stress wave that propagates through the bar. After transmission, the stress wave is reflected at the incident bar-specimen-transmission bar interface. The strain gauge on the incident bar records the incident (In.) & reflected (Re.) signals, and the one on the transmission bar records the transmitted (Tr.) signal.

The PDC cutter auxiliary device used for the SHPB test is designed, as shown in Fig. 6(b), to study the rock fragmentation efficiency under impact loads. A PDC cutter auxiliary device for the SHPB testing system was designed (Xi et al., 2025). The apparatus comprises a metal sleeve, replacement heads with varying back rake angles, and a PDC cutter. The metal sleeve is arranged on the right side of the incident bar that impacted specimens, and various replacement heads could be fixed at the right end of the metal sleeve. A replacement head with a back rake angle of 20° is fixed to obtain a more obvious impact effect in the study (Liu et al., 2021).



(a) SHPB testing system



(b) PDC cutter auxiliary device

Fig. 6. The composition of the experimental device and the size of the accessories.

The angle between the upper surface of the PDC tooth and the impact direction was kept at 20°. The PDC cutter is fixed on the replacement head by bolts to avoid detachment in the test process. For easier obtainment of impact fragments without considering the circumferential pressure, the specimens are wrapped using a rubber sleeve in the test. The diameters of specimens and replacement heads are identical (50 mm). A 16 mm-diameter PDC tooth with a height of 13 mm is installed at the replacement head. After installing the metal sleeve on the incident bar, the centers of the metal sleeve, incident bar, replacement head, PDC cutter, specimen, and transmission bar are aligned on the same horizontal line.

The SHPB dynamic compression and Bit-SHPB tests are carried out on thermal-treated granite using the devices presented in Fig. 6. For quantitative assessment of the effect of impact loading on the HDR drilling efficiency, the influences of various temperatures and cooling treatments on the compression failure characteristics and rock-breaking volume are analyzed. Since percussion tools usually have critical impact velocities in the range of 4–9 m/s, the velocities in the SHPB dynamic compression and Bit-SHPB tests were separately set to 8.0 and 6.0 m/s, based on prior studies related to loading rate in dynamic impact tests (Li et al., 2005; Dai et al., 2016). During impact, the strain rate has an approximate range between 80 and 120 s⁻¹.

3. Experimental results

3.1. Drillability value of granite

Drillability value K_d , as a crucial indicator for the difficulty of breaking rocks, can be calculated by utilizing the regression model of the drilling time of the rock drillability test. The formulas are as follows:

$$K_d = \log_2 t + G_i \quad (1)$$

$$G_i = 2^{i-1} - 1 \quad (2)$$

where K_d denotes the drillability value. t is the drilling time of the rock drillability test. G_i denotes the equivalent conversion level. i is the WOB level (in this study, the WOB is level 1, $i = 1$, $G_1 = 0$).

Every specimen was subjected to the drillability test, which tested the upper and lower sides of the rock. Fig. 7 presents the statistical outcomes. The ribbon areas in the figure represent the calculation drillability value K_d of both the upper and lower surfaces of the test specimen, whereas the data points indicate the average value.

It can be observed that the granite has a K_d value of about 6.17 at room temperature. With the temperature rise, K_d decreases progressively. The decrease rate is slow initially, then gradually accelerates as the temperature approaches 300 °C. At 600 °C, the K_d of granite under different cooling treatments is 2.44, 2.34, and 2.24, respectively, about 60% lower than at room temperature. At the same temperature, the K_d of LN₂-cooled granite is smaller, while its drillability is stronger. Therefore, the drillability ranking for the thermal-treated granite cooled by different media is: LN₂ cooling > water cooling > natural cooling.

3.2. Dynamic mechanical properties of granite

In the SHPB dynamic compression test, the air pressure was set to 0.25 MPa consistently, and the impact bar was launched from the same position each time to ensure that the impact velocity was maintained at approximately 8.0 m/s. Fig. 8(a) illustrates the typical SHPB stress-time curve recorded during the test. The

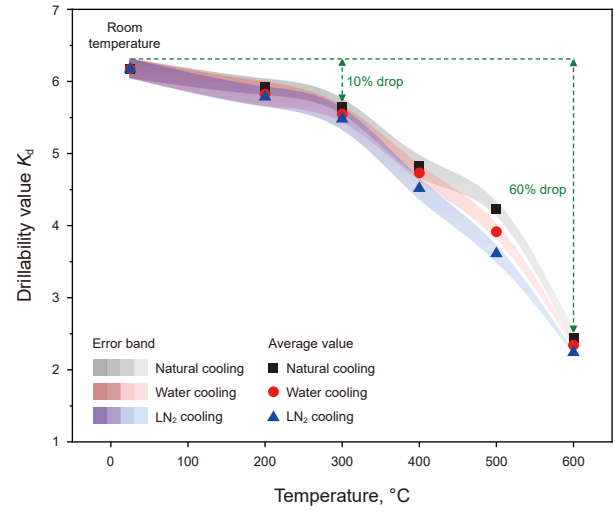


Fig. 7. Effects of various cooling treatments on the drillability value.

incident, reflected, and transmitted parts in the curve are put together for comparison, as displayed in Fig. 8(b). Clearly, the sum of the incident wave (In.) and the reflected wave (Re.) is equal to the transmitted wave (Tr.), confirming that the dynamic stress equilibrium was achieved. In addition, the dynamic stress equilibrium of all granite specimens has been checked.

3.2.1. The stress-strain curve

According to previous studies and one-dimensional stress wave theory (Han et al., 2022; Lou et al., 2024), separate computation of the stress $\sigma(t)$, strain $\epsilon(t)$, and strain rate $\dot{\epsilon}(t)$ in the SHPB compression test is obtained using the following formulas upon reaching dynamic stress equilibrium:

$$\begin{cases} \sigma_C(t) = \frac{A_0 E_0 (\epsilon_I + \epsilon_R + \epsilon_T)}{2A_S} \\ \epsilon_C(t) = \frac{C_0}{B} \int_0^t (\epsilon_I - \epsilon_R - \epsilon_T) dt \\ \dot{\epsilon}_C(t) = \frac{C_0}{B} (\epsilon_I - \epsilon_R - \epsilon_T) \end{cases} \quad (3)$$

where A_0 is the cross-sectional area of the incident and transmission bars. A_S and B are the cross-sectional area and the thickness of the specimen. E_0 signifies the elastic modulus for the impact, incident, and transmission bars; C_0 denotes the P-wave velocity for incident and transmission bars; ϵ_I , ϵ_R , and ϵ_T refer to the incident, reflected, and transmitted strains.

Following the SHPB compression test, the dynamic stress-strain curves for granite were contrasted by Eq. (3), as depicted in Fig. 9. Obviously, the trends of the curves are roughly identical. The peak stress of the curves decreases progressively with the rising temperature. This is mainly caused by the emergence and development of internal microcracks in the rock. On the contrary, the peak strain of the curve increases with increasing temperature because of the rock's plasticity enhancement and brittleness weakening. At an identical temperature, the variation law of peak stress under different cooling methods is natural cooling > water cooling > LN₂ cooling.

3.2.2. Dynamic strength and Young's modulus

The dynamic mechanical properties of granite can be employed to reflect the degree of internal damage and the difficulty of rock

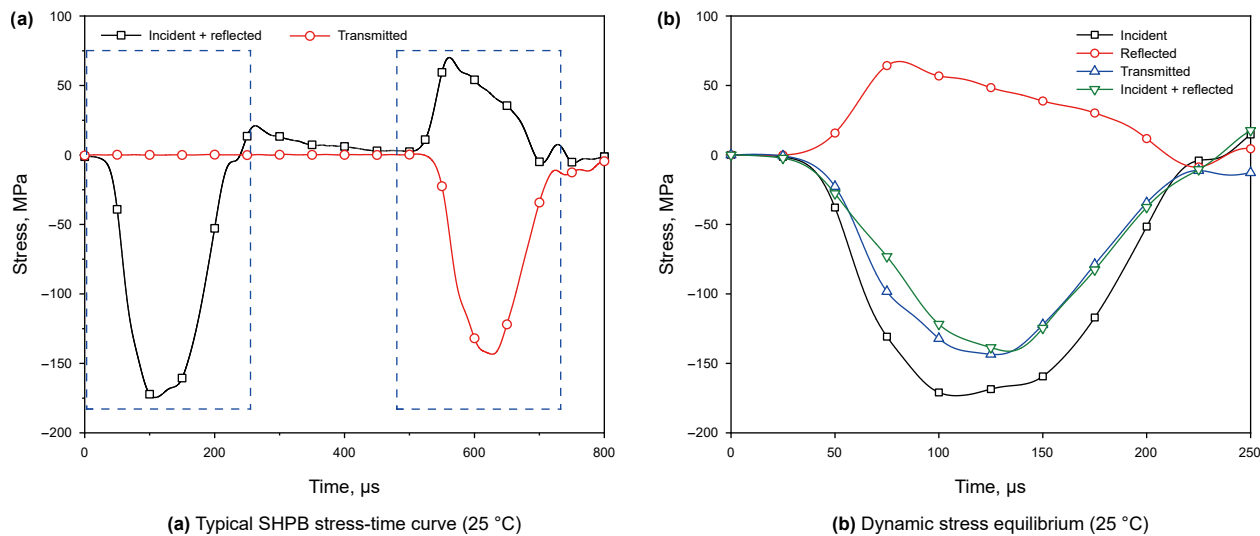


Fig. 8. Dynamic stress balance check for the granite specimen.

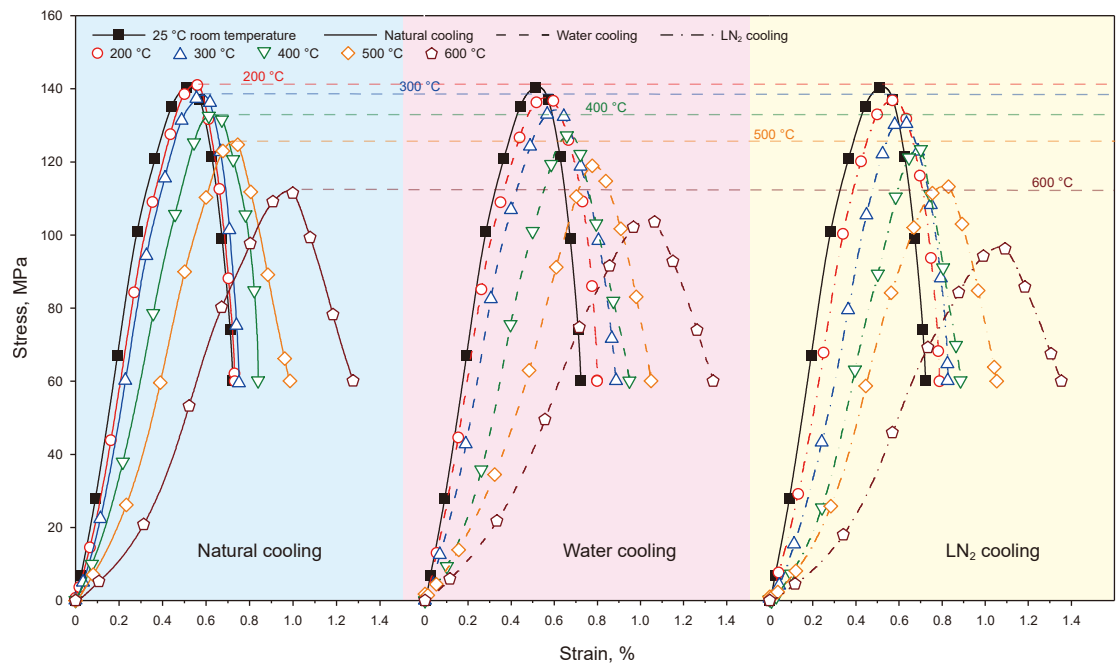


Fig. 9. Dynamic stress-strain curves under different treatments.

breaking. The dynamic compressive strength of granite is numerically equal to the peak stress. Relevant calculation of Yang's modulus is shown in Eq. (4) (Fan et al., 2022):

$$E_s = \frac{\sigma_{0.6} - \sigma_{0.4}}{\varepsilon_{0.6} - \varepsilon_{0.4}}$$

(4)

where E_s denotes the dynamic Young's modulus. $\sigma_{0.6}$ and $\sigma_{0.4}$ refer to 60% and 40% of peak stress, respectively, then $\varepsilon_{0.6}$ and $\varepsilon_{0.4}$ refer to the corresponding strains.

Table 1 details the calculation outcomes, whereas Fig. 10 presents the power function fitting curves of the two for different temperatures. With increasing temperature, the dynamic compressive strength and Young's modulus of rock show a downward trend. The latter fitting curve exhibits a greater

secant slope than the former, showing a higher sensitivity of Young's modulus to temperature than dynamic compressive strength.

Table 1

Dynamic properties of thermal-treated granite after various cooling treatments.

Cooling temperatures, °C	Dynamic strength, MPa			Young's modulus, GPa		
	Natural	Water	LN ₂	Natural	Water	LN ₂
25	140.50	140.50	140.50	40.69	40.69	40.69
200	141.22	137.67	136.84	38.67	37.98	36.79
300	138.28	134.22	131.21	37.28	35.68	32.56
400	132.87	127.34	123.99	33.87	31.01	28.31
500	125.67	119.04	113.67	27.29	24.09	22.64
600	112.02	104.34	96.72	19.37	15.72	14.16

Taking natural cooling as an example, the Young's modulus and dynamic strength of granite at room temperature (25 °C) are 140.5 MPa and 40.69 GPa, respectively. Upon reaching 600 °C, the relevant parameters decrease to 112.02 MPa and 19.37 GPa, respectively, which are 20.27% and 52.40% lower compared to the values at room temperature. It is because as the most abundant component in granite, quartz undergoes an α - β phase transition at temperatures around 573 °C (Fan et al., 2017). At this point, anisotropic mineral expansion and differential thermal expansion occur between the quartz grains and the rest of the minerals, which cause an increase and expansion of the microcracks, resulting in a rapid decrease in strength and deformation resistance.

Various cooling treatments also influence the granite's dynamic properties at the same temperature. The dynamic compressive strength and Young's modulus of specimens under natural cooling are always the highest, followed by water cooling, and LN₂ cooling is the lowest. This is mainly caused by the rapid cooling effect, which makes the granite's temperature drop faster than that of natural cooling. This cold quenching effect significantly reduces the granite's brittleness and increases its plasticity.

3.3. Dynamic strength varies with drillability

Rock strength influences its drillability, affecting the ROP of the drilling tool during percussive drilling. To explore the relationship between rock strength and drillability, the dynamic strength variation with drillability value K_d of the thermal-treated granite subjected to various cooling treatments was examined by linear fitting, as displayed in Fig. 11.

The dynamic strength of granite is proportional to the drillability value K_d . The greater the rock strength, the higher the K_d value and the worse the drillability. When the same strength is maintained, the drillability of granite under three cooling

treatments is also different. It can be inferred that strength is not the only factor affecting drillability; other factors, such as lithology, rock temperature, rock environment, and so on, also affect drillability.

3.4. Bit-SHPB test results of granite

3.4.1. Typical stress-time curves

Air pressure in the Bit-SHPB test is designed as 0.25 MPa consistently, and the striker bar is fired from the identical location each time to keep the speed of the incident bar at about 6.0 m/s. Fig. 12(a) compares the typical stress-time curves recorded in the SHPB and Bit-SHPB tests at 25 °C.

It can be observed that the shape of the reflected wave in the Bit-SHPB test is not a regular sine wave. Due to the point-to-point contact between the specimen and the PDC cutter, the cutting force changes continuously during the impact. The peak value of the transmitted wave in the Bit-SHPB test is much smaller than that in the SHPB test, and the take-off point of the former is slightly delayed compared with the latter.

As shown in Fig. 12(b) and (c), due to material impedance differences between the metal bud, PDC cutter, and granite specimen, stress waves undergo both transmission and reflection phenomena when passing through the interfaces between the metal bar and drill tooth, between the tooth and specimen, and between the specimen and metal bar, respectively. This sequentially generates reflected waves 1 to 3 and transmitted waves 1 to 3. Throughout the entire process, the PDC cutter auxiliary device installed on the incident bar is considered part of the same assembly as the bar itself during analysis, as both components are made of the same alloy material and are seamlessly integrated. This effectively explains why the stress history curves in Bit-SHPB test exhibit irregular fluctuations compared to the conventional SHPB test.

The stress-time curves of thermal-treated granite in the Bit-SHPB test were calculated. It can be seen from Fig. 12(d–f) that, compared with the incident wave, different treatments have a greater influence on the reflected and transmitted waves of rock.

3.4.2. Analysis of energy conversion

Energy is absorbed and transformed during rock cutting and breakage in the Bit-SHPB test. Analyzing the energy change during rock breakage exerts a guiding role in enhancing HDR mining

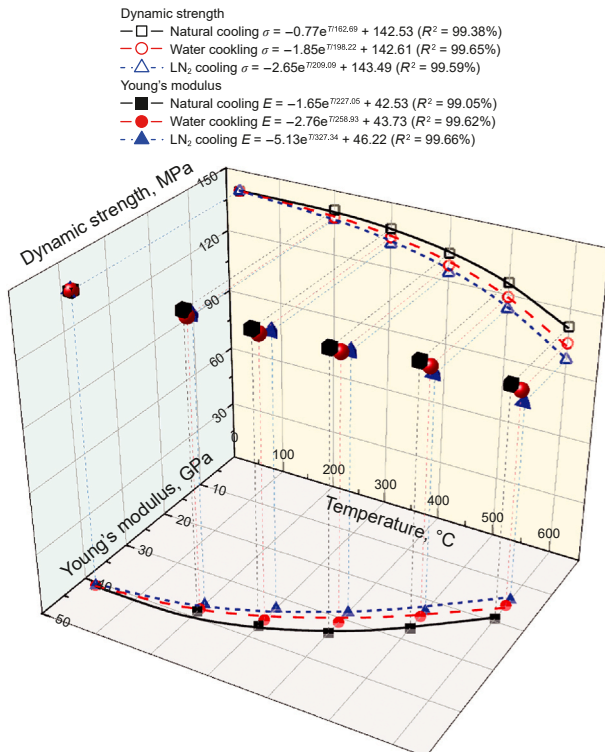


Fig. 10. Effects of various cooling treatments on granite's dynamic properties.

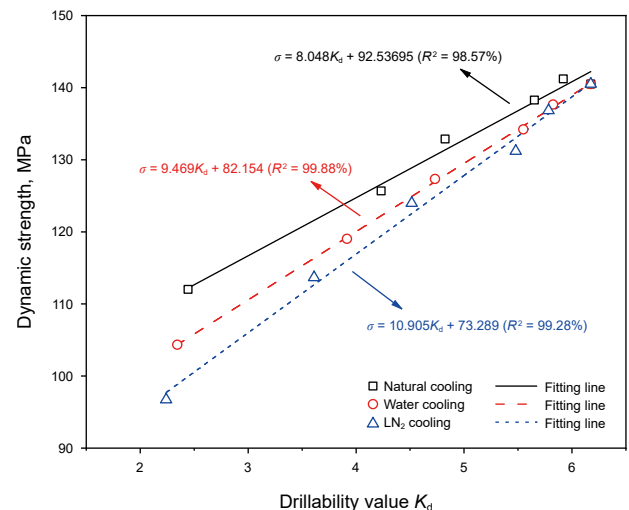


Fig. 11. The variation of dynamic strength with drillability value of granite.

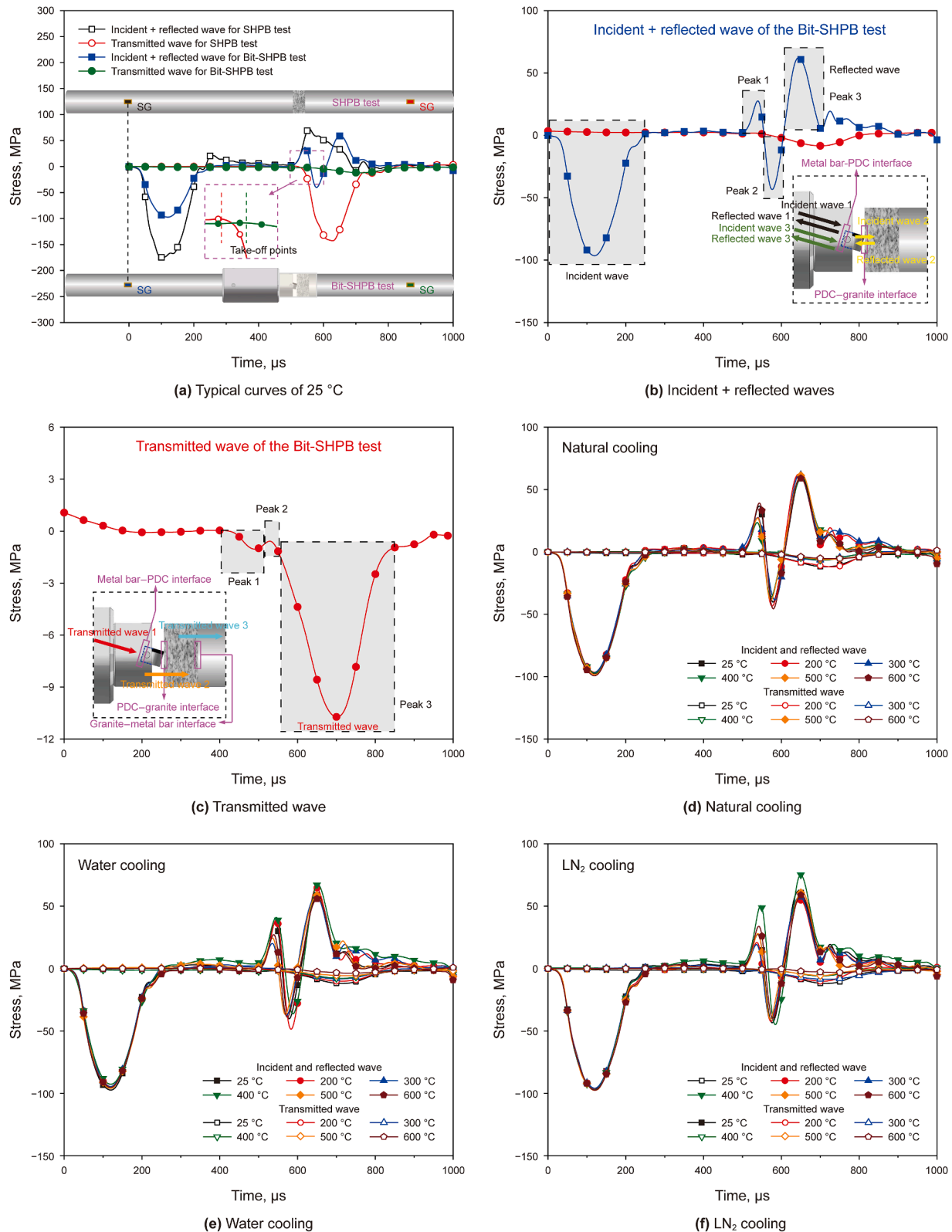


Fig. 12. Typical stress-time curves for Bit-SHPB test.

performance and reducing drilling costs in practical engineering (Ji et al., 2023).

The first law of thermodynamics holds that energy conversion is the fundamental characteristic of rock deformation and failure,

which are prompted by the key processes of energy accumulation, transmission, and dissipation (Xi et al., 2023a). According to the one-dimensional elastic wave and energy conservation theories, we can obtain the incident, reflected, transmitted, and absorbed

energies during the Bit-SHPB test with Eqs. (5)–(8) (Song et al., 2022):

$$W_I(t) = (A_0 C_0 / E_0) \int_0^t \sigma_I^2(t) dt \quad (5)$$

$$W_R(t) = (A_0 C_0 / E_0) \int_0^t \sigma_R^2(t) dt \quad (6)$$

$$W_T(t) = (A_0 C_0 / E_0) \int_0^t \sigma_T^2(t) dt \quad (7)$$

$$W_A(t) = W_I(t) - W_R(t) - W_T(t) \quad (8)$$

where $W_I(t)$, $W_R(t)$, and $W_T(t)$ denote the incident, reflected, and transmitted energies, respectively. $\sigma_I(t)$, $\sigma_R(t)$, and $\sigma_T(t)$ signify the amplitudes of incident, reflected, and transmitted stresses at time t , respectively. Absorbed energy $W_A(t)$ approximately equal to dissipated energy $W_D(t)$.

According to the formula above, the corresponding reflected, transmitted, and absorbed energies are estimated as described in Fig. 13. The energy-time curves under different temperatures and cooling methods all exhibit the characteristics of slowly rising first, then rapidly rising, and finally reaching a stable value. For different energies, there are the following rules.

- (I) As the temperature rises, the reflected and transmitted energies of the PDC cutter gradually decrease, while the absorbed energy progressively increases during crushing granite. When the temperature remains the same, it can be found along the dotted line in the figure that the reflected and transmitted energies of natural cooling are the highest, while their absorbed energy is the lowest. The LN₂ cooling exhibits the highest absorbed energy and the lowest reflected and transmitted energies.
- (II) Compared with the reflected energy curves, those of transmitted and absorbed energies are smoother. It's because the contact surface continuously changes during the impact, causing the waveform of the reflected wave to change as it passes through the PDC cutter and the rock. In addition, the correlation among the three energies is: absorbed energy > reflected energy > transmitted energy. Table 2 lists the calculation results of the three energies.

3.4.3. Morphology characteristics of the impact craters

The impact of the PDC cutter will leave a crater on the rock surface similar to the tooth's shape. By comparing the sizes of impact craters, the penetration depth and drilling ability of PDC teeth can be quantitatively assessed (Yagiz, 2009). After the Bit-SHPB test, the granite specimens were collected and recombined along the cracks to compare the degree of damage to the rocks caused by the PDC cutter.

To better display the impact craters and cracks, the surface of the granite was scanned by 3D scanning technology, as presented in Fig. 14. Taking the room temperature granite as an example, the PDC cutter impacting will not only leave prominent impact craters but also produce tensile cracks that extend along the specimen. At the same impact velocity, the impact craters of specimens subjected to different temperatures and cooling methods exhibit distinct differences. These differences are primarily manifested in the size of the impact craters and the direction of crack propagation, although the shape of the impact craters generally remains triangular.

To further quantify the changes in the impact crater, the point clouds of the impact crater reconstructed using 3D scanning technology were calculated, and layered results on the granite surface were selected for analysis. The change of the apparent area of thermal-treated granite under three cooling methods is shown in Fig. 15.

The apparent area value of the impact crater generated by the PDC cutter is further counted, as shown in Fig. 15(d). The apparent area gradually increases with the increase in temperature, and reaches the highest value at 600 °C. In the process of temperature elevation, the evident area under LN₂ cooling is always larger than that under the other two methods. At 600 °C, the apparent area under three cooling methods is 4.12 (natural), 4.33 (water), and 5.34 (liquid nitrogen) times higher than that at room temperature, respectively.

Apart from the apparent area of the impact crater, the PDC cutter penetration depth along the impact direction is also an indicator for measuring the drill tooth's performance in breaking rocks. A three-dimensional (3D) model of an impact crater is reconstructed by 3D scanning technology, as shown in Fig. 16(a). Then, Fig. 16(b–d) show the impact crater variations by analyzing the reconstruction model's point cloud data. The penetration depth of the impact crater varies with the heating temperature and cooling treatment of each specimen.

The maximum and average depth of the impact craters generated by the PDC cutter were further statistically analyzed, as shown in Fig. 16(e). The maximum depth can characterize the penetration depth, while the average depth can characterize the magnitude of the tangential force exerted on the drill tooth. The maximum and average depths of impact craters both increase gradually with rising temperature. At the same temperature, LN₂ cooling treatment results in the most significant penetration depth, followed by water cooling, with natural cooling being the lowest. The maximum depths at 600 °C under natural, water, and LN₂ cooling are 2.69, 2.90, and 3.09 times higher compared to the room-temperature values, respectively.

Referring to the rock damage caused by projectile penetration in dynamics, when the quality, material, and impact velocity of the PDC cutter remain unchanged, the factors affecting the apparent area and penetration depth of the crater are the traits of the rock material itself (Peng et al., 2018). The impact crater exhibits a gradually increasing apparent area and penetration depth as the heating temperature increases. It's because the temperature rise deepens the initial cracks and damage inside the rock, reducing its strength. The combined effects of thermal shock and rapid cooling progressively enhance the rock's plasticity. Besides, the failure duration is also prolonged, which would cause more severe damage to the rock (Xi et al., 2023a).

4. Discussion

4.1. Analysis of failure characteristics of the impact crater

4.1.1. Comparison between the theoretical and actual volume

When analyzing the 3D reconstruction model of an impact crater, it is found that the shape of craters obtained by impacting is different under the same speed and back rake angle. As a typical brittle rock, granite mainly exhibits brittle failure under the joint effects of impact loading and cutting force. However, as the temperature rises, the brittleness of granite is gradually reduced, while its plasticity is gradually enhanced (Zhang et al., 2016; Li et al., 2024).

The shape of the impact surface is irregular under the action of impact loads, and the difference between the theoretical and the

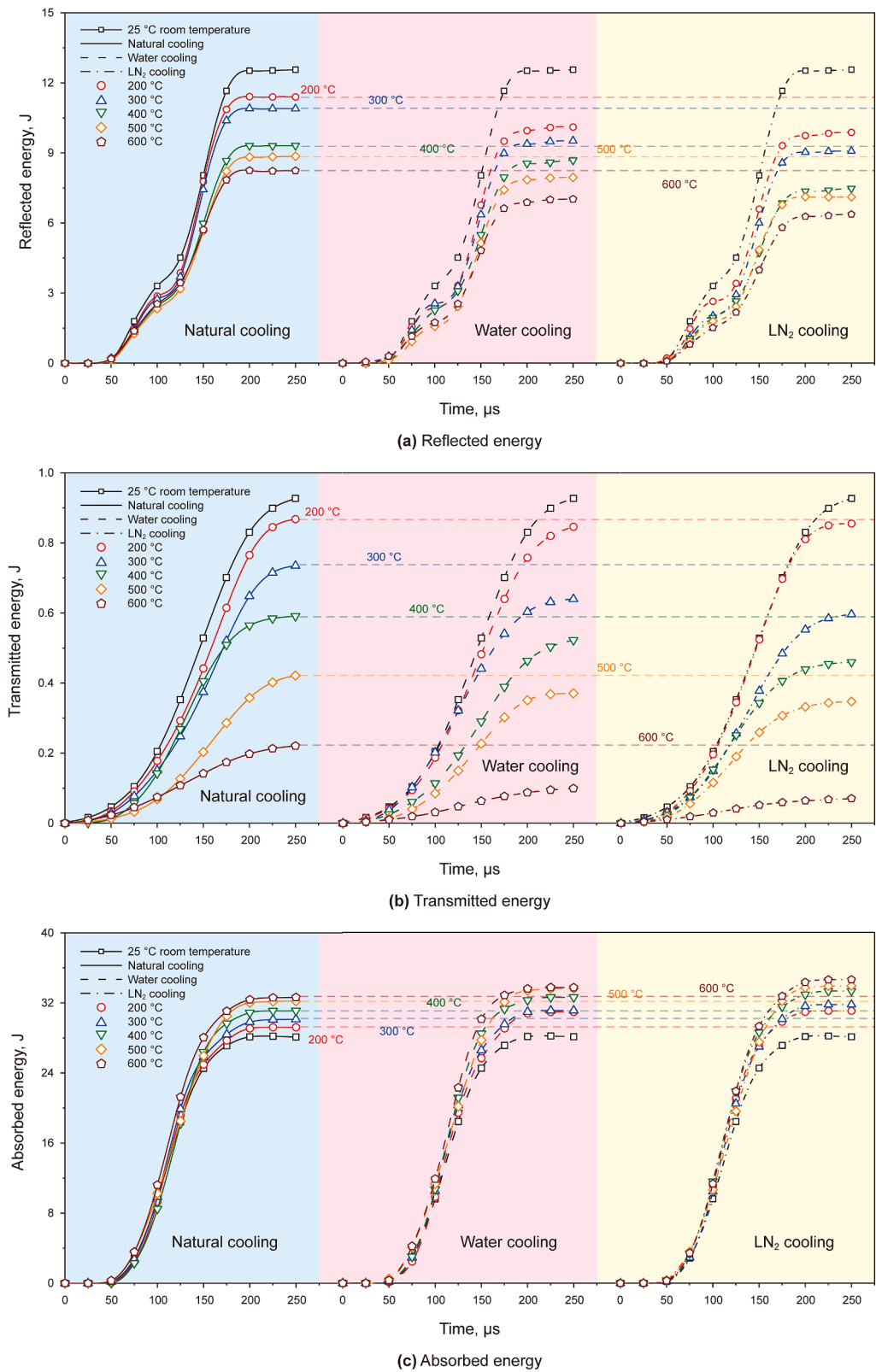


Fig. 13. Different energy-time curves of granite in the Bit-SHPB test.

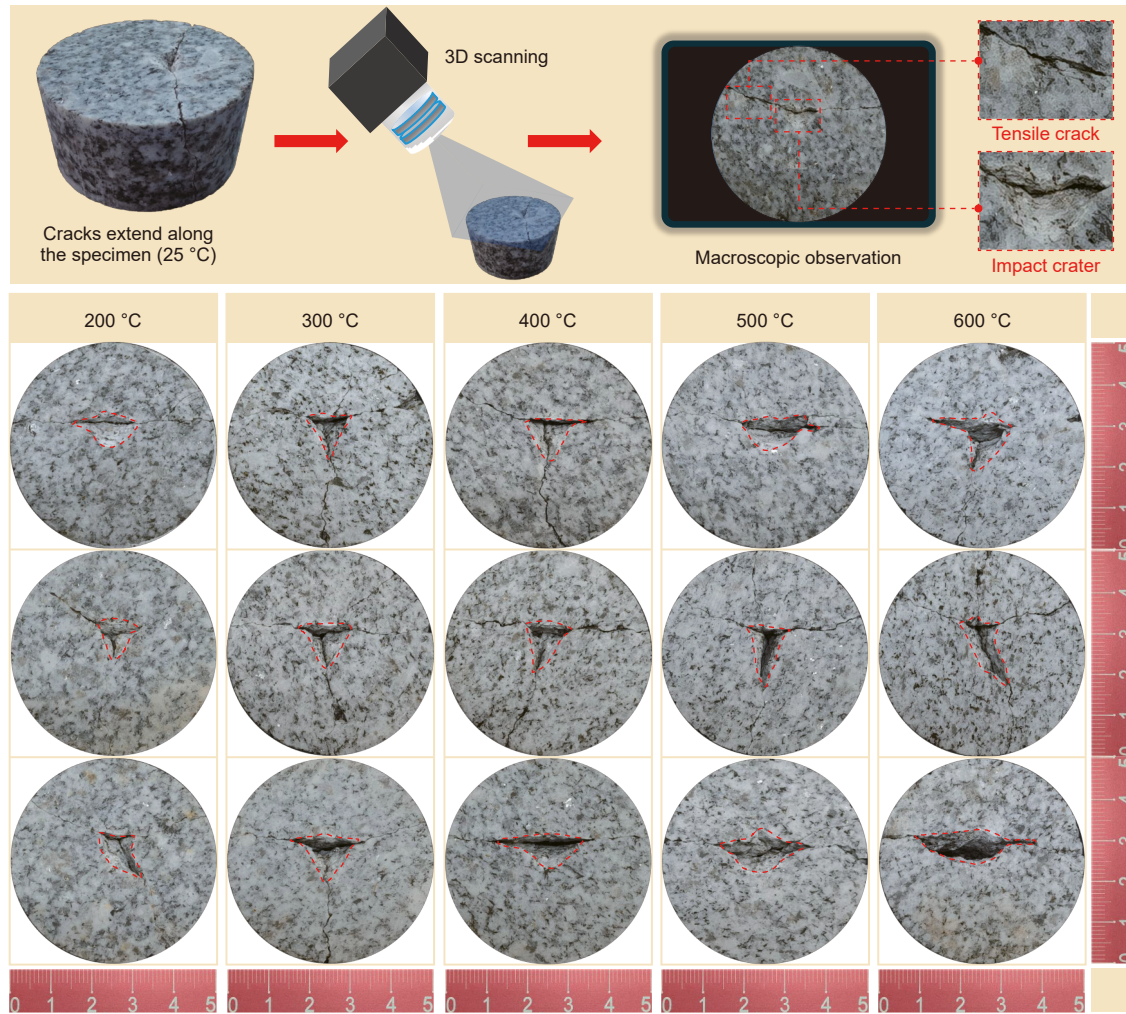


Fig. 14. Apparent observations of impact craters.

actual impact surface is shown in Fig. 17(a). In addition, the characteristics of dynamic intrusion in terms of impact volume can be mainly divided into the following two aspects: I The kinetic energy generated by the initial velocity increases the penetration depth of the PDC cutter ($d_A > d_T$); II The instantaneous high stress caused by the initial velocity leads to rapid crack initiation and propagation, thereby increasing the fracture area. As shown in Fig. 17(b), the force exerted by the PDC cutter on the rock can be decomposed into horizontal (F_{x-up} and F_{x-down}) and vertical forces (F_{y-up} and F_{y-down}). The horizontal force is used to crush the rock and produce cracks, while the perpendicular force is used to chip the rock fragments and expand the impact volume.

To compare the effects of dynamic impact intrusion with those of static intrusion, the theoretical impact area was selected to be the same as the actual impact area measured in Fig. 15(d). The area can be converted to volume and considered as the theoretical impact volume through geometric calculations (details were recorded in Appendix A). The tested PDC cutter has a height of 13 mm, a diameter of 16 mm, and its back rake angle θ is 20° . The calculating formula of theoretical impact volume is shown in Eqs. (9)–(11). Appendix B records the detailed formula derivation process.

$$V_{\text{Theoretical}} = \begin{cases} \frac{2}{3}(R^2 - x_0^2)^{\frac{3}{2}} \cot \theta + x_0 R^2 \cot \theta \arcsin \frac{x_0}{R} + x_0^2 \sqrt{R^2 - x_0^2} \cot \theta - \frac{\pi}{2} x_0 R^2 \cot \theta & (0 < d \leq 4.446) \\ \frac{2}{3}(R^2 - x_0^2)^{\frac{3}{2}} \cot \theta + x_0 R^2 \cot \theta \arcsin \frac{x_0}{R} + x_0^2 \sqrt{R^2 - x_0^2} \cot \theta - \frac{\pi}{2} x_0 R^2 \cot \theta - \frac{2}{3}(R^2 - x_1^2)^{\frac{3}{2}} \cot \theta \\ - x_1 R^2 \cot \theta \arcsin \frac{x_1}{R} - x_1^2 \sqrt{R^2 - x_1^2} \cot \theta + \frac{\pi}{2} x_1 R^2 \cot \theta & (d > 4.446) \end{cases} \quad (9)$$

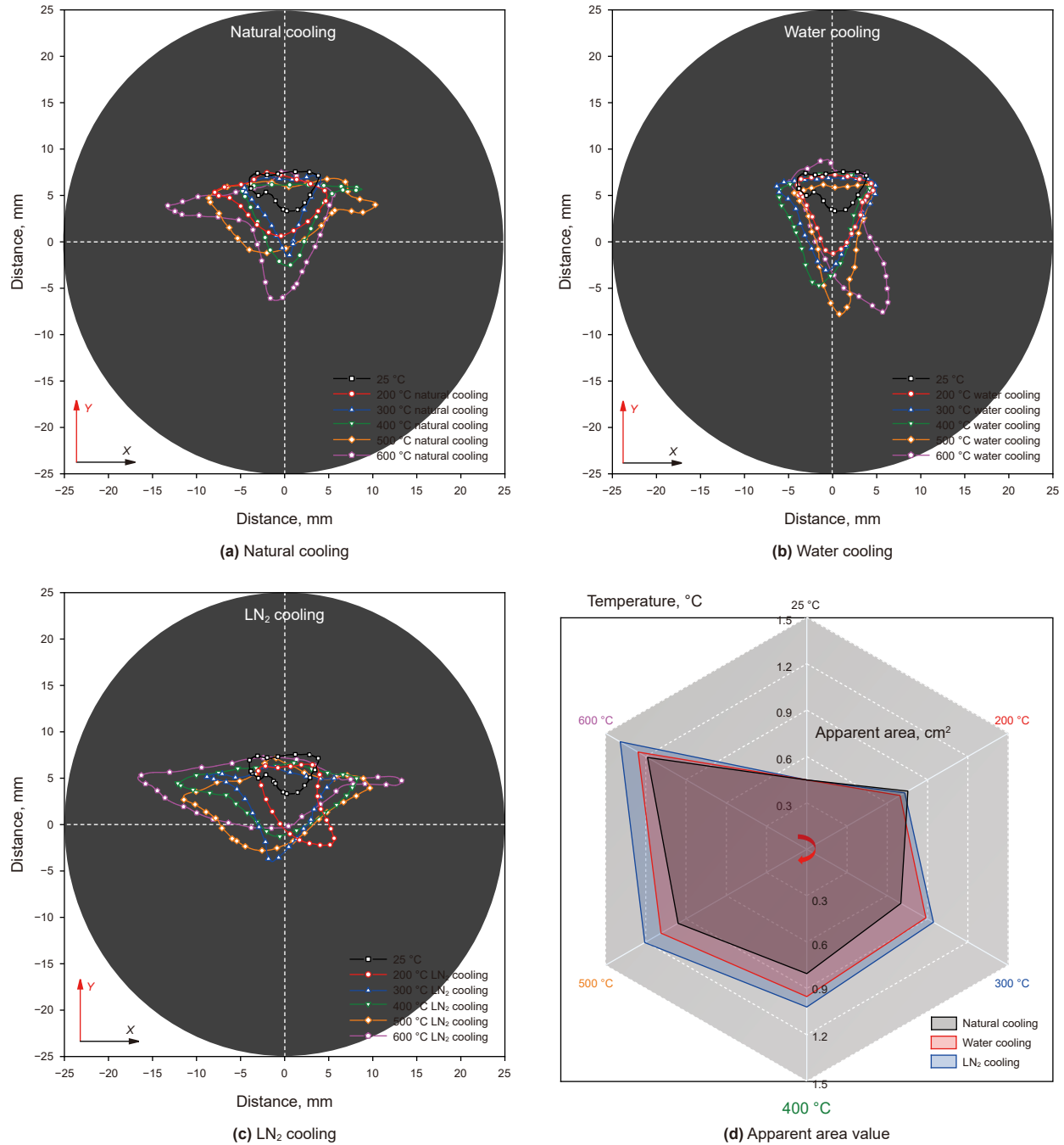


Fig. 15. Apparent area of the impact craters under various cooling methods.

$$x_0 = R - d/\cos\theta \quad (10)$$

$$x_1 = R - d/\cos\theta + L\tan\theta \quad (11)$$

where R represents the radius of the PDC cutter. θ and L respectively represent its back rake angle and height.

x_0 and x_1 depend on the penetration depth d , which can be calculated using Eqs. (10) and (11).

The theoretical impact volume under various temperatures and cooling treatments is calculated using a formula, and the actual impact volume can be obtained by 3D scanning technology. Fig. 18 compares the two volumes.

Fig. 18(a) shows the division between the actual and theoretical volume of the impact crater under the same impact area. The blue part is the calculated theoretical volume, and the black texture part is the actual volume. Under room temperature and 200 °C conditions, the proportion of the two volumes is close; the theoretical failure part is destroyed in the impact test. With the temperature increase, the overlapping part of the two volumes decreases. Due to the increased plasticity of the granite, impact damage and crack propagation occur more frequently, resulting in the actual damage volume of the rock far exceeding the theoretical one.

Fig. 18(b) displays the calculated values for the impact crater's theoretical and actual volumes, and an exponential function fits the

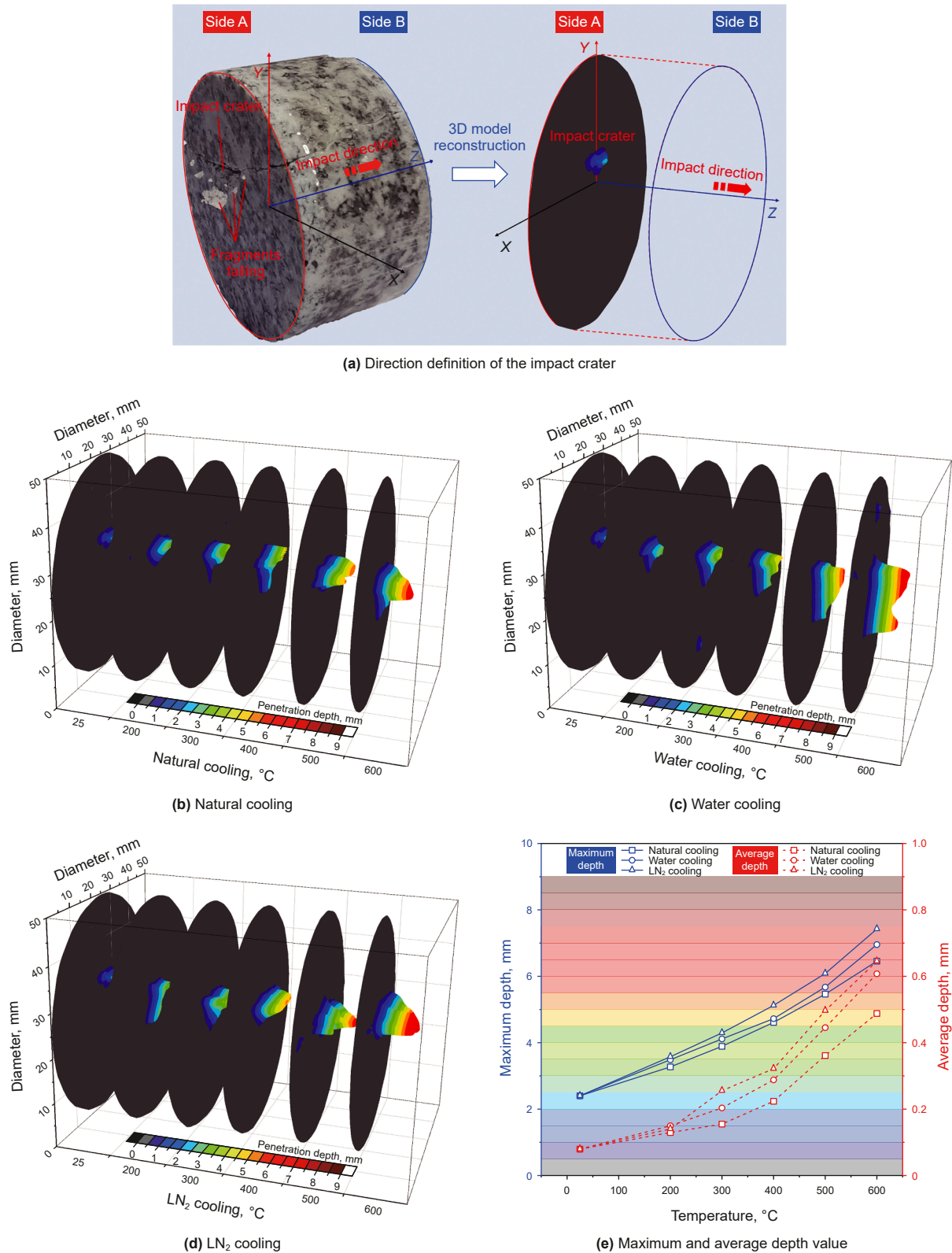


Fig. 16. Elevation maps of impact craters under various cooling methods.

results. Both volumes increase with the temperature elevation, with the actual volume increasing faster. When the temperature is the same, the two failure volumes are the largest under LN₂ cooling, followed by water cooling, while the smallest is under natural cooling.

To explore the erosion capability of PDC cutter against thermal-treated granite under dynamic loading conditions, thereby enhancing the compatibility between drilling tools and formations in HDR environment, the dynamic magnification factor of

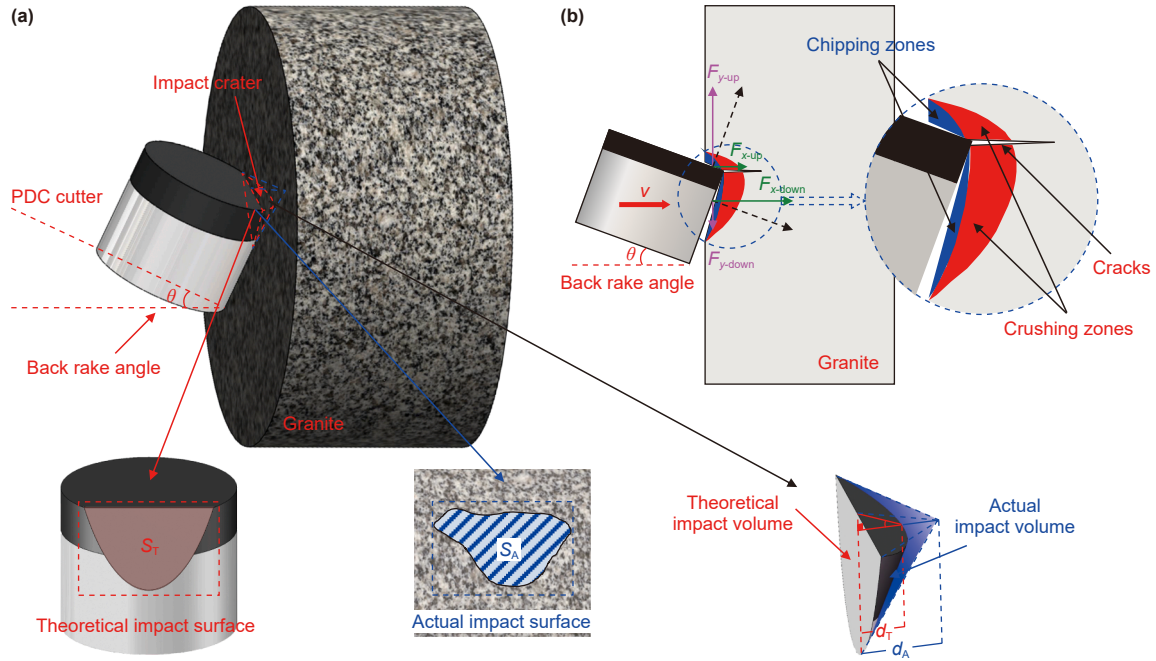


Fig. 17. The failure mode of rock by PDC cutter under impact loads.

intrusion β_1 is defined to assess the rock failure by drill teeth at different temperatures, which can be formulated as:

$$\beta_1 = \frac{V_A}{V_T} \times 100\% \quad (12)$$

where V_A and V_T represent the actual volume and theoretical volume of the impact crater, respectively.

Fig. 19 shows the effects of various temperatures and cooling treatments on the β_1 value of granite. The logistic regression function is used to fit the points in the figure, and the coefficient of determination (COD) for fitting curves is above 92.00%, implying that the curves can better reflect the change rule.

It can be found in Fig. 19 that under the same cooling treatments, the dynamic magnification factor of granite with temperature can be divided into three stages.

- (I) At this stage (25–200 °C), granite's dynamic magnification factor β_1 increases slowly. It can be found that the β_1 value is slightly larger than 1.0 at 25 °C, which indicates that the actual volume is slightly larger than the theoretical volume. The primary way of rock failure after impact loading is brittle failure.
- (II) At this stage (200–500 °C), granite's dynamic magnification factor β_1 increases rapidly. When the temperature rises to 500 °C, the β_1 value increases by 130% compared to 25 °C. The increase in the factor indicates that the temperature rise will cause a decrease in brittleness and an enhancement in plasticity for granite, thus further expanding the gap between the actual impact volume and the theoretical impact volume. This is because when the heating temperature is low, there are few microcracks and pores in the granite, and the fracture mode has high predictability. As the temperature rises, more and more thermal damage and microcracks in granite will affect its failure path, resulting in the connected parts of cracks in the rock being more prone to destruction upon impact loading.

- (III) At this stage (above 500 °C), granite's dynamic magnification factor β_1 tends to be stable. When the temperature reaches 600 °C, the deterioration of the mechanical properties and the development of internal pores of granite are more thorough than in the low temperature period. At this point, the growth rate of the β_1 value slows down accordingly.

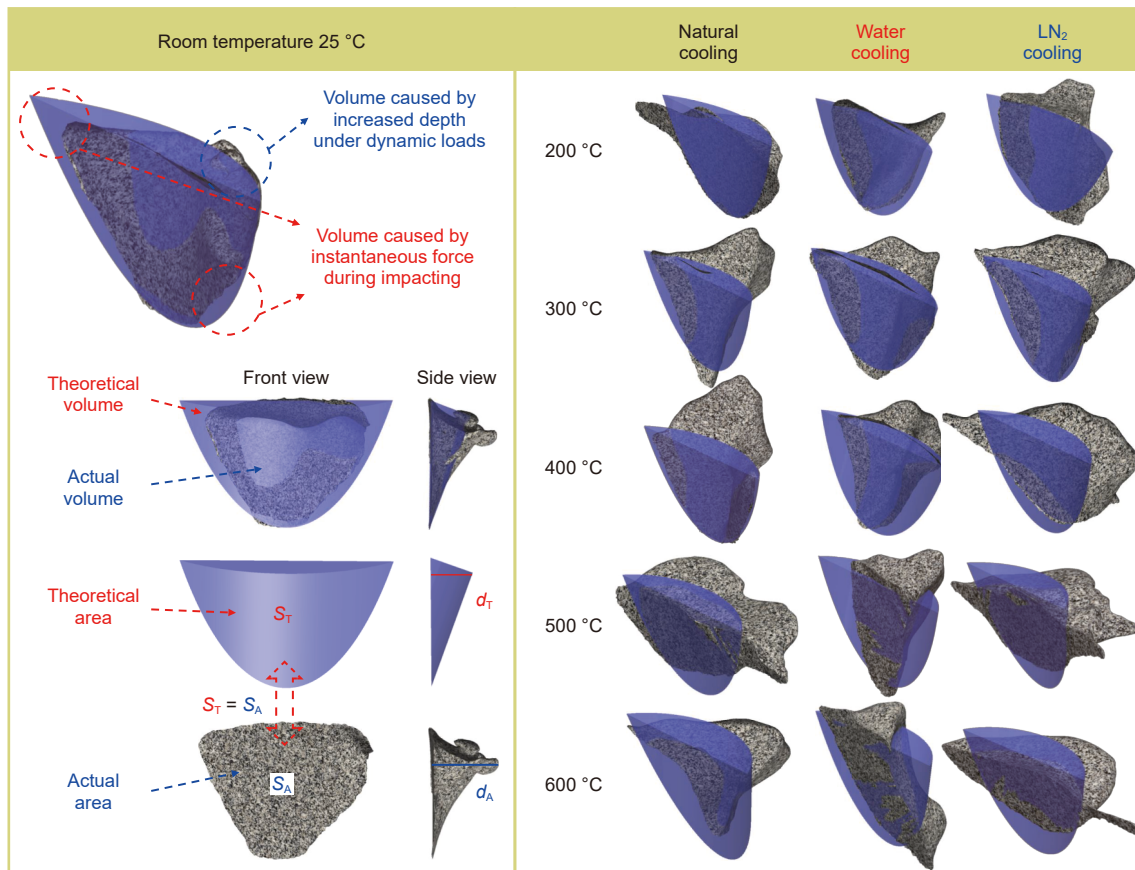
In addition, the dynamic magnification factor β_1 exhibits a similar upward trend for granite with different cooling methods. At identical temperatures, the β_1 of LN₂ cooling is always smaller than that of water and natural cooling, suggesting that the damage caused by rapid cooling will also affect the transformation of rock brittleness and plasticity. To quantitatively evaluate the correlation of the thermal shock damage with its dynamic magnification effect, it is necessary to calculate the thermal shock damage D_T of granite further.

4.1.2. Influence of thermal damage on the dynamic magnification factor

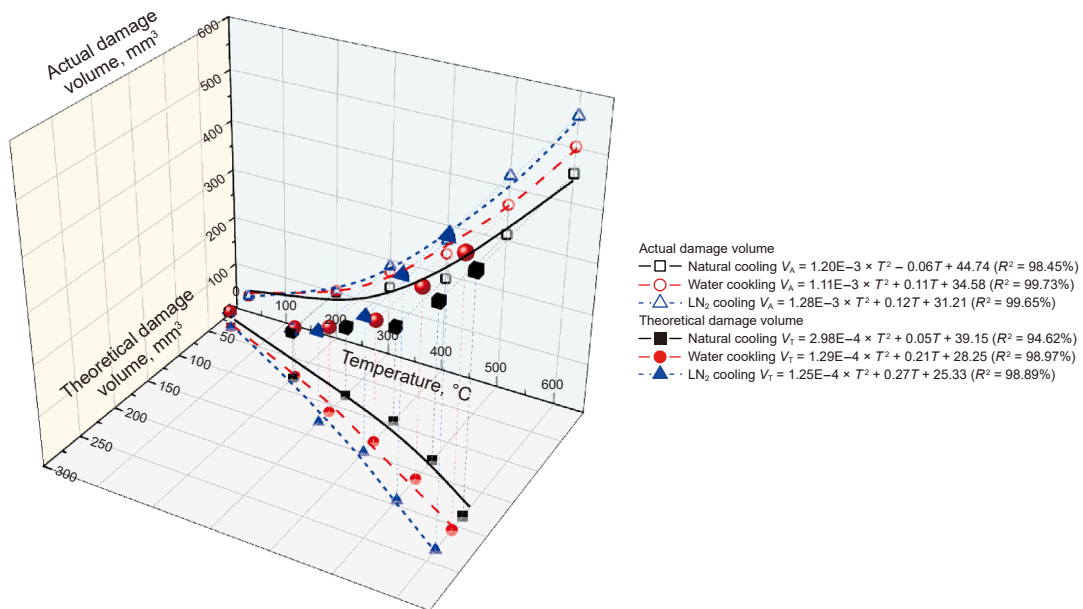
Heating and rapid cooling treatment can cause severe thermal shock damage to the granite specimens, reducing the rock's mechanical and physical behavior. Therefore, the influence of internal microcracks and pores on granite is quantitatively elaborated by introducing the degree of thermal shock damage. In prior research, the velocity of P-wave in rock is closely associated with the rock's damage (Liu et al., 2025). A greater rate of P-wave velocity alteration indicates severe rock damage. Hence, the P-wave velocity-related thermal damage value D_T can be used for evaluating the degree of rock damage (Hu et al., 2022), as described in Eq. (13):

$$D_T = 1 - \frac{\rho_1 c_1^2}{\rho_0 c_0^2} \quad (13)$$

where ρ_0 and ρ_1 represent the density of rock before and after heating. c_0 and c_1 represent the P-wave velocity of rock before and after heating.



(a) The division between actual volume and theoretical volume



(b) Calculation of actual and theoretical volume

Fig. 18. Comparison between the two impact volumes at identical area ($S_T = S_A$).

Thermal shock damage is calculated based on granite's density and P-wave velocity measurements before and after thermal-cooling treatment. Table 3 details the calculation results.

Thermal shock damage value D_T reflects the size of the damage caused by thermal stress on the rock, which exemplifies the

deterioration effect of heating and cooling treatments on the rock. Fig. 20 shows the relationship between granite's dynamic magnification factor β_I and D_T . Linear regression analysis has been performed on all data points in the figure, and the corresponding confidence regions and prediction bands were drawn. The

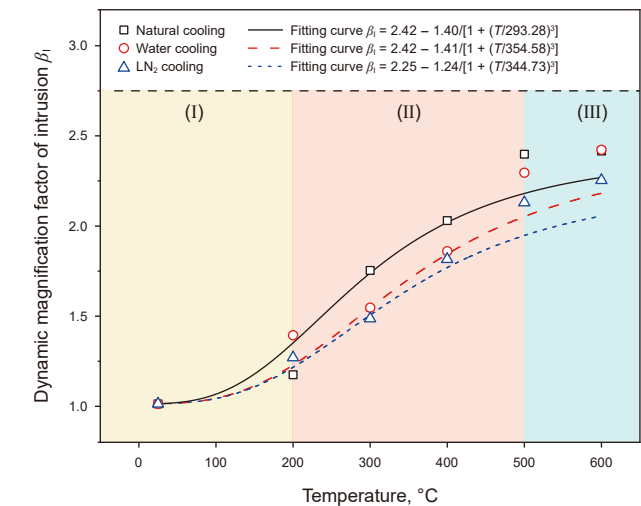


Fig. 19. Variation trend of the dynamic magnification factor β_I versus temperatures.

dynamic magnification effect equation of granite is shown in Eq. (14), and the COD of the fitting curve exceeds 90.77%, implying that the curve can better reflect the change law.

$$\beta_I = 0.864 + 1.547D_T \tag{14}$$

where β_I denotes the dynamic magnification factor of intrusion of granite. The higher the value of β_I , the more sensitive the rock is to dynamic loads and the more severe the damage. D_T represents the thermal shock damage of granite.

As shown in the figure, the dynamic magnification factor of intrusion varies in direct proportion to thermal shock damage. β_I value approaches 1.0 when thermal damage is minor, and granite primarily undergoes brittle fracture. When the thermal damage value approaches 1.0, the actual impact volume of granite is approximately 2.3 times the theoretical impact volume, at which point the failure of rock is gradually transformed into plastic failure.

4.2. Average fragment size and fractal dimension

4.2.1. Distribution regulation of the fragment size

The volume of impact craters generated by the impact load and PDC cutter has been comprehensively analyzed, while the damage volume after impact is not a whole, but a combination of

Table 3
The calculation results of thermal damage D_T .

Temperature, °C	Cooling methods	Density, g/cm ³		P-wave velocity, m/s		D_T
		ρ_0	ρ_1	c_0	c_1	
25	/	2.628	2.628	4950	4950	0
200	Natural	2.628	2.625	4938	4268	0.254
	Water	2.627	2.623	4945	4076	0.322
	LN ₂	2.628	2.622	4950	3906	0.379
300	Natural	2.629	2.620	4950	3702	0.442
	Water	2.628	2.617	4950	3460	0.513
	LN ₂	2.628	2.615	4962	3284	0.564
400	Natural	2.628	2.611	4950	2976	0.641
	Water	2.628	2.603	4950	2694	0.707
	LN ₂	2.626	2.600	4958	2492	0.749
500	Natural	2.628	2.592	4950	2238	0.798
	Water	2.627	2.582	4944	1892	0.856
	LN ₂	2.628	2.577	4950	1663	0.889
600	Natural	2.629	2.559	4938	1219	0.941
	Water	2.628	2.549	4950	1072	0.955
	LN ₂	2.628	2.543	4955	858	0.971

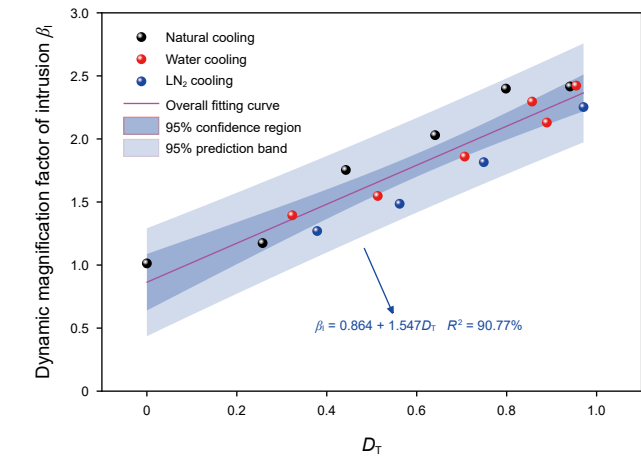


Fig. 20. Variation trend of the dynamic magnification factor β_I versus thermal damage D_T .

fragments of different sizes, as illustrated in Fig. 21. The size and distribution of the rock fragments are different with the changing temperature.

Table 2
The energy of heated granite after various cooling treatments.

Temperature, °C	Cooling methods	Loading rate, s ⁻¹	Incident energy, J	Reflected energy, J	Transmitted energy, J	Absorbed energy, J
25	/	67.09	41.74	12.72	0.92	28.10
200	Natural	66.47	41.48	11.39	0.87	29.22
	Water	67.89	41.88	10.40	0.86	30.62
	LN ₂	67.56	41.80	9.88	0.86	31.06
300	Natural	67.26	41.77	10.89	0.74	30.14
	Water	66.73	41.26	9.52	0.64	31.10
	LN ₂	66.82	41.45	9.08	0.60	31.77
400	Natural	66.64	41.14	9.15	0.59	31.40
	Water	66.56	41.81	8.98	0.57	32.26
	LN ₂	67.3	41.25	7.48	0.45	33.32
500	Natural	67.28	41.60	8.97	0.43	32.20
	Water	67.34	41.94	7.95	0.37	33.62
	LN ₂	67.26	41.36	7.11	0.35	33.90
600	Natural	66.44	41.09	8.24	0.22	32.63
	Water	67.02	40.83	7.02	0.10	33.71
	LN ₂	66.80	41.07	6.38	0.07	34.62

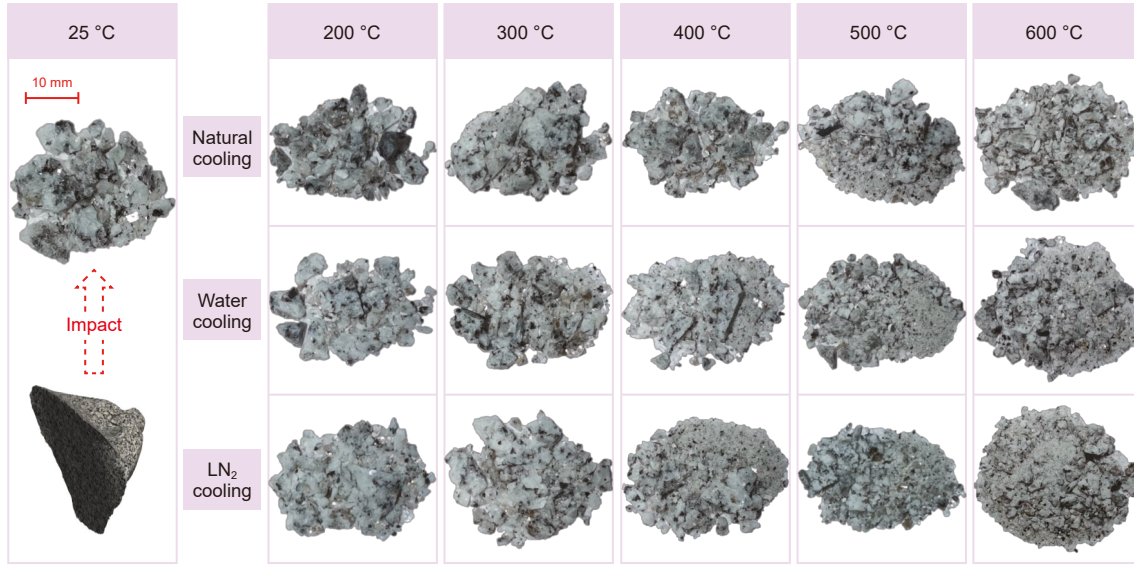


Fig. 21. Breaking fragments of thermal-treated granite.

Fig. 21 shows that with the increase in temperature, the number of massive coarse fragments decreases, and the number of fine fragments dominated by powder increases. The average fragment size of rock specimens can well describe the irregular fragment distribution following the impact of thermal-treated granite (Yin et al., 2022). Due to the small size of granite debris after impact loading, standard sieves varying in aperture (0.2, 0.5, 1.0, 2.0, 5.0 mm) were used for screening tests, so that the rock fragmentation degree could be assessed quantitatively. To better elucidate the fragmentation degree, the average size of fragments d_m is formulated as (Zhao et al., 2023):

$$d_m = \frac{\sum d_i M_i}{\sum M_i} \quad (15)$$

where d_i signifies the average fragment size in standard sieves varying in aperture. M_i represents the fragment mass percentage corresponding to d_i .

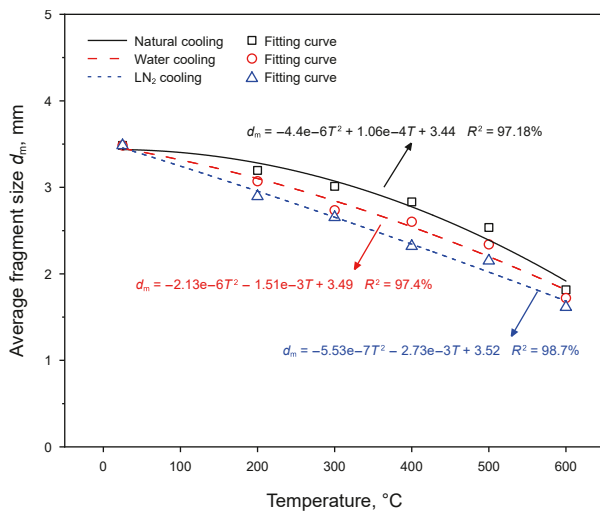


Fig. 22. Evolution of average fragment size d_m under various cooling treatments.

Fig. 22 shows the average fragment size d_m change of heated granite under various cooling treatments, and the results are fitted by quadratic functions. According to the fitting results, the d_m value of the specimen decreases nonlinearly with the increase in temperature, and the overall degree of granite fragmentation increases progressively. Upon reaching 600 °C, the average fragment sizes of granite under three cooling treatments are 1.82, 1.72, and 1.61 mm, respectively, which are more than 45% lower than those at room temperature. This shows that high temperature significantly affects the expansion of internal damage to granite. Notably, during the heating process, the d_m under natural cooling remains maximum, followed by water cooling, while LN₂ cooling remains minimum. This indicates that rapid cooling increases granite's fragmentation degree within a specific range, with the average fragment size affected by heating and cooling treatments.

4.2.2. Fractal dimension analysis of impact fragments

Although the d_m value can reflect the average particle size of rock fragments, it fails to express the holistic characteristics of fragment distribution intuitively. In other words, the weight of the fragments represented by the same d_m in the sieve may differ, reducing the quantification of the fragment distribution characteristics. Recent years have witnessed the broad application of the fractal theory in rock mechanics (Li et al., 2022). To facilitate the fragmentation characterization of rock impacted by the PDC cutter, the distribution features are evaluated by the fractal dimension D . Based on the mass-frequency correlation, the distribution equation of the impact fragmentation of rock can be obtained as follows:

$$\frac{M(x)}{M(T)} = \left(\frac{x}{x_m} \right)^{3-D} \quad (16)$$

where $M(x)$ and $M(T)$ separately denote the cumulative fragment mass underneath the sieve and the total mass. x represents the fragment size, x_m signifies the maximum particle size of fragments, and D represents the fractal dimension of the fragment distribution.

By simultaneously taking the logarithms on both sides of Eq. (16), the simplified formula can be obtained:

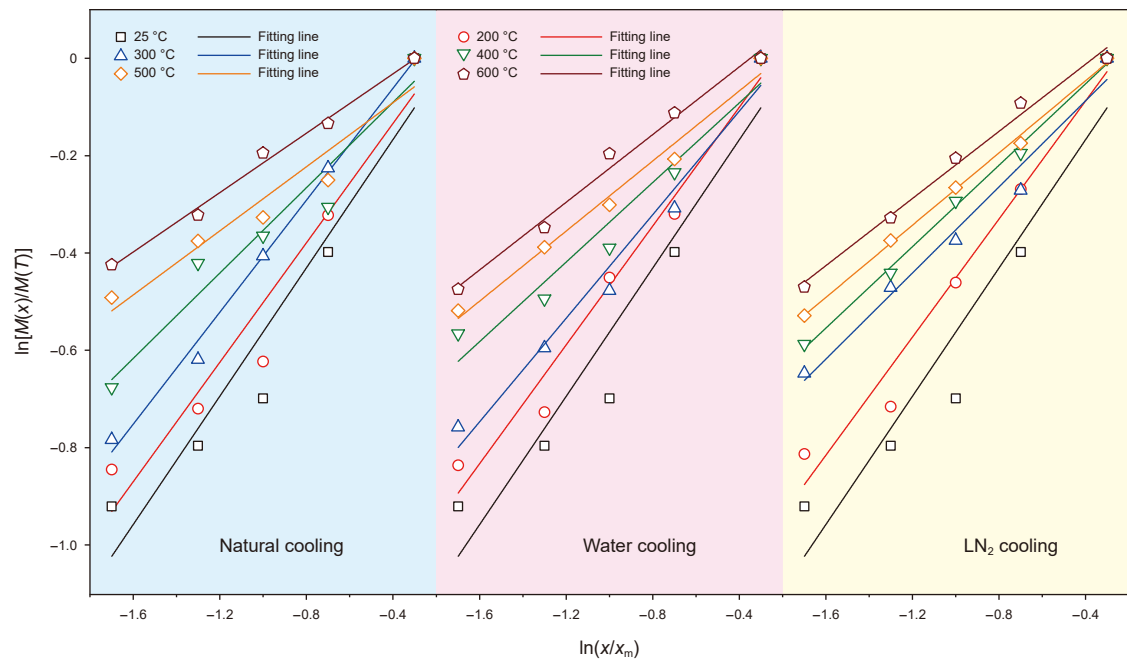


Fig. 23. lg[M(x)/M(T)]-lg(x/x_m) curves of fragmentation distribution.

Table 4
Results of the fractal dimension D.

Temperature, °C	Cooling methods	Average fragment size d _m , mm	Fractal dimension D	Correlation coefficient R ²
25	/	3.484	2.341	91.764%
200	Natural	3.195	2.387	93.802%
	Water	3.071	2.390	96.298%
	LN ₂	2.896	2.393	96.509%
300	Natural	3.011	2.425	96.445%
	Water	2.735	2.468	96.849%
	LN ₂	2.653	2.558	98.226%
400	Natural	2.832	2.561	94.217%
	Water	2.603	2.587	96.294%
	LN ₂	2.319	2.598	98.512%
500	Natural	2.536	2.661	92.649%
	Water	2.341	2.640	97.721%
	LN ₂	2.151	2.629	99.63%
600	Natural	1.816	2.685	98.037%
	Water	1.720	2.652	98.505%
	LN ₂	1.614	2.655	98.733%

$$\ln[M(x)/M(T)] = (3 - D)\ln(x/x_m) \tag{17}$$

Fig. 23 illustrates the double logarithmic coordinate system for thermal-treated granite fragments subjected to varying cooling conditions. The positions for each point under three cooling methods are relatively consistent with the Rosin Rammler function distribution, suggesting that the distribution of the fragments has good statistical self-similarity (Wu et al., 2018). The least squares approach accomplished data fitting. The fitted line had a slope of (3–D), while the COD for the fitted line met the requirements. According to the calculation of the slope of Fig. 23, we can obtain the fractal dimension D, and Table 4 details the calculation outcomes. As the temperature rises, the fitting line slope tends to decrease. In other words, the D value increases, and the fragmentation of rocks becomes severe.

Fig. 24 shows the function relationship with the fractal dimension D as the function and the thermal shock damage D_T as the independent variable. The logistic regression model is

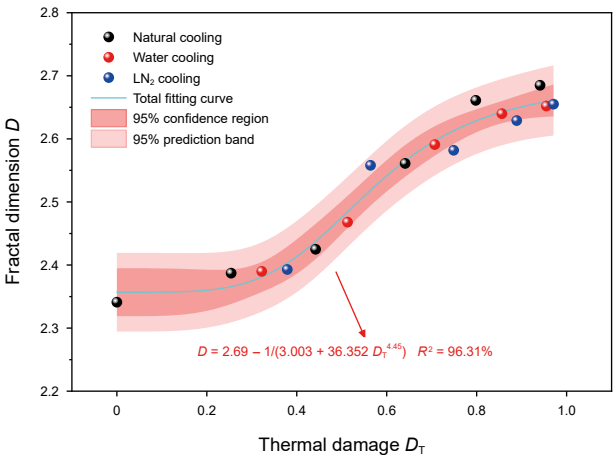


Fig. 24. Variation trend of the fractal dimension D versus thermal damage D_T.

employed to fit all points in the figure, then plot the 95% confidence region and prediction band. The fractal dimension calculation equation of granite is shown in Eq. (18), and the COD for fitting the curve is above 96%, implying that the curve can better reflect the change rule.

$$D = 2.69 - \frac{1}{3.003 + 36.352 \times D_T^{4.45}} \quad (18)$$

where D denotes the fractal dimension of thermal-treated granite. A greater value of D indicates severe damage to granite and a higher complexity of fragment components. D_T represents the thermal shock damage of granite.

The results in Fig. 24 show that with the progressive intensification of thermal shock damage D_T inside the granite, the fractal dimension D of granite fragments under the PDC cutter impact also shows a gradual increase. According to the fitting curve properties, when the D_T of granite is between 0 and 0.4, the D of impact fragments increases slowly, only about 2.42% higher than that of the room-temperature granite. When the granite D_T value is between 0.4 and 0.8, the D of impact fragments increases rapidly. When the value of D_T is equal to 0.8, the D of impact fragments is approximately 11.56% higher than the room-temperature value. When the D_T is close to 1.0, the D value increase rate tends to be gentle.

This change rule is because when the thermal shock damage of granite specimens is low, the internal pores and microcracks are fewer, and the damage degree is lighter under the PDC cutter impact. In addition, the granite strength changes insignificantly when the temperature is lower; thus, the fractal dimension's growth rate is slow. When the thermal shock damage is high, the internal microcracks and pores are more interconnected to form the failure path, along which the rock is more easily destroyed, causing a slower growth rate of the fractal dimension. When the temperature is at the middle level, the thermal shock damage inside the granite begins to increase, but it has not been connected. Therefore, there are many possibilities for the final failure path and mode, so the growth rate of the fractal dimension of the rock is relatively rapid.

4.3. Analysis of energy conversion in Bit-SHPB test

4.3.1. Energy transfer efficiency

When using percussive drilling tools for rock breaking, increasing the speed helps enhance the rock-breaking efficiency, despite the accelerated wear of key components and shortened service life of the percussive drilling tool (Wei et al., 2022). Similarly, during the drilling in HDR, wearing of the PDC teeth occurs when the teeth interact with the high-temperature rock. The PDC teeth wear is diverse under different temperatures and cooling treatments.

When the impact speed remains unchanged, we can judge the PDC cutter wear using the energy conversion efficiency η during the drill teeth–rock interaction. A greater η value indicates a lower degree of cutter wear and a longer lifespan of the percussive drilling tool (Ma et al., 2023). Therefore, thoroughly considering the rock η value during breakage is required when studying the compatibility of the percussive drilling tool, bit tooth, and formation rock. The calculation formula is as follows:

$$\eta = \frac{W_A(t)}{W_I(t)} \times 100\% \quad (19)$$

where $W_A(t)$ and $W_I(t)$ represent the rock's absorbed and incident energies at time t , respectively.

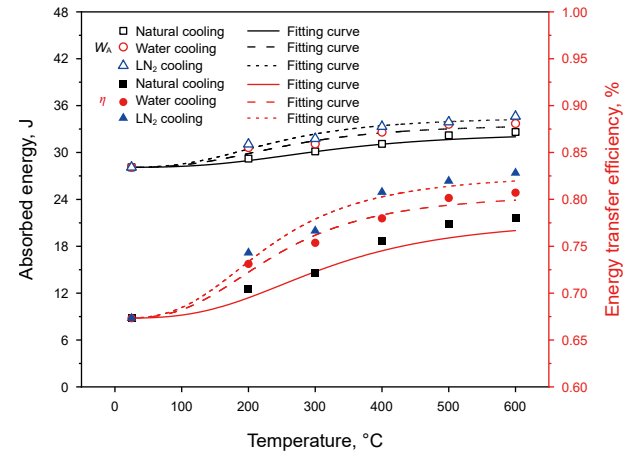


Fig. 25. Energy transfer efficiency of granite under different cooling methods.

Fig. 25 shows the change in energy transfer efficiency of thermal-treated granite cooled with various media, where the left and right ordinate axes separately denote the final value of absorbed energy and the energy transfer efficiency η . The logistic regression model was used to fit all points. The results demonstrate that the changing trend of the energy transfer efficiency under impact loading with temperature is similar to the final value of absorbed energy, which increases slowly first, then rapidly, and finally tends to be gentle. The η of rock at 600 °C is about 16% higher when compared with the room-temperature value. The reason is that the increase in temperature makes the rock impact volume by the PDC cutter larger, and the fragments are broken into smaller fragments, so more energy must be absorbed.

For granite under various cooling treatments, the change law of energy transfer efficiency η of granite is: LN₂ cooling > water cooling > natural cooling at the same temperature. It can be concluded that the rapid cooling treatment has a specific effect on the PDC cutter service life during the rock breakage. The main principle is to reduce the rock strength using water or low-temperature drilling fluid; thus, the rock is more likely to be thoroughly destroyed. Finally, the smaller fragments produced by the PDC cutter are also easily separated from the drilling bit and discharged from the bottom hole, which is beneficial for cleaning the wellbore.

4.3.2. Rock-breaking specific energy

To further analyze the effect of the energy generated by the PDC cutter under impact load, in addition to the impact crater parameters and energy transfer efficiency measured above, the rock-breaking specific energy δ under the action of drill teeth should be calculated as the evaluation standard for rock-breaking performance of various PDC teeth (Xiong et al., 2023). The calculation formula is as follows:

$$\delta = \frac{W_A(t)}{V_A} \quad (20)$$

where $W_A(t)$ represents the absorbed energy of the rock at time t . This energy contains the energy consumed by the generation of impact craters and crack propagation. V_A signifies the volume of the impact crater and extended macro-cracks. As the volume of the crack is difficult to determine, it does not distinguish between these two volumes in the research, both of which are regarded as the volume of the impact crater.

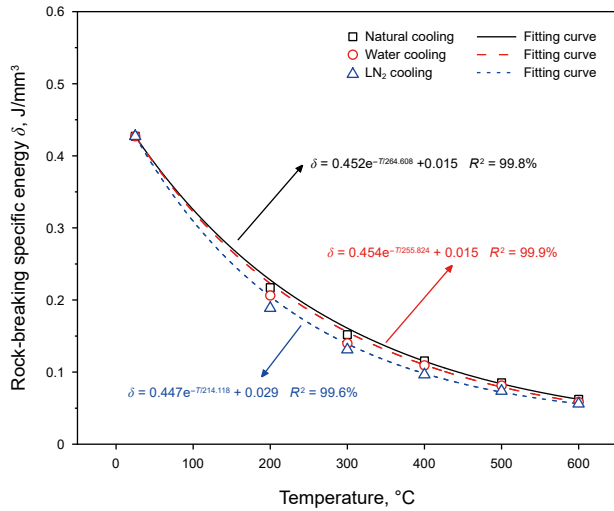


Fig. 26. Specific energy of granite under different temperatures and cooling methods.

Based on Eq. (20), the rock-breaking specific energy under impact loading is estimated, and the outcomes are fitted by exponential functions, as illustrated in Fig. 26. According to the results, as the temperature rises, the δ value for the granite tends to decrease nonlinearly, that is, the energy consumed for damaging the same volume is lowered. At a 600 °C temperature, the δ of granite cooled with three media is 0.062, 0.059, and 0.056 J/mm³, respectively, which is more than 80% lower than the room temperature. This indicates a prominent influence of high temperature on the degree of damage to granite specimens. The energy absorbed by crushed granite increases when the temperature rises, but the impact volume increases faster, and thus the rock-breaking specific energy decreases. It is worth noting that during the heating process, the δ value of rock under natural cooling is always the highest, followed by water cooling, while the lowest is under LN₂ cooling. This indicates that rapid cooling increases granite's impact volume within a specific range, and the δ value of granite is affected by both temperature and cooling methods.

Fig. 27 shows a functional relationship with normalized rock-breaking specific energy δ_N as the function and the thermal shock damage D_T as an independent variable. All points are fitted by the power function in the figure, and the corresponding confidence regions and prediction bands were drawn. The definition

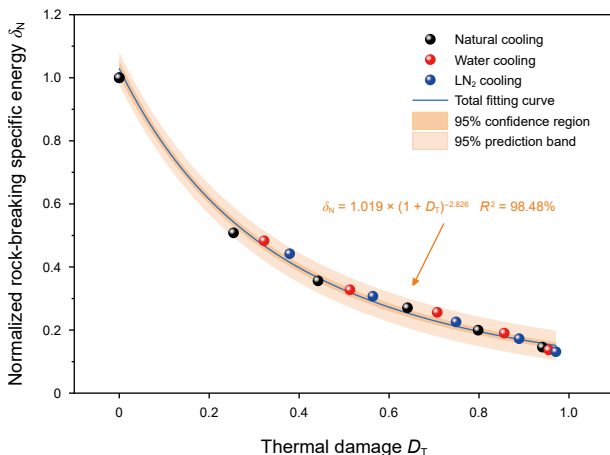


Fig. 27. Variation trend of normalized specific energy δ_N versus thermal damage D_T .

of normalized rock-breaking specific energy and the fitting equation can be seen in Eqs. (21) and (22), respectively. And the COD for fitting the curve is above 98.00%, implying the ability of the curve to reflect the change law better.

$$\delta_N = \frac{\delta}{\delta_0} \quad (21)$$

$$\delta_N = 1.019 \times (1 + D_T)^{-2.826} \quad (22)$$

where δ represents the rock-breaking specific energy of granite, with a greater value indicating the necessity of more energy absorption by the same breaking volume of granite; δ_N denotes the normalized δ value of granite; δ_0 represents the δ value of granite at room temperature; D_T indicates the thermal shock damage of granite.

The figure shows that as the thermal shock damage gradually increases, the specific energy of granite under the PDC cutter impact is slowly reduced. Based on the fitting curve properties, as the D_T increases, the granite δ_N value gradually shifts from rapid to slow decline. At thermal shock damages less than 0.4, the δ_N is reduced by about 60% compared with the rock at room temperature. When the D_T is between 0.4 and 1.0, the δ_N of granite shows slow reduction.

This change rule is because thermal shock damage is an important indicator that affects the strength of granite. When the granite has low thermal shock damage, the volume of damage under the impact of the PDC cutter is small, and the rate of increase in impact volume with temperature is also low. At this time, the change rate of granite absorbed energy with temperature is higher than that of volume, leading to a faster growth rate of the δ value. When the granite has high thermal shock damage, its strength decreases drastically, while the impact volume of the PDC cutter increases rapidly. At this time, the change rate of granite absorbed energy with temperature is lower than that of volume, so the growth rate of δ progressively slows down.

5. Conclusions

A dynamic rock-breaking test is undertaken on granites treated at varying heating temperatures (200, 300, 400, 500, 600 °C) and by varying cooling techniques (natural cooling, water cooling, LN₂ cooling) with the utilization of the SHPB system installed with the PDC cutter. The dynamic compressive strength and drillability of granites with various heating and cooling treatments are calculated, the impact crater volume and depth after penetration are analyzed, the energy evolution of thermal-treated granite impacted by PDC cutter is discussed, and the variation of dynamic magnification factor, fractal dimension & rock-breaking specific energy of granite with thermal damage under impact load is revealed. The main conclusions are as follows.

- (1) The mechanical behavior of granite after heating and cooling treatments is studied. According to the drillability test results, with temperature rising, the drillability value K_d of granite is reduced when the drillability increases. According to the SHPB test results, the Young's modulus and the dynamic compressive strength of granite are reduced as the temperature rises. Besides, the granite drillability is decreased gradually as its strength is enhanced. The reduction rate of granite's drillability under natural cooling is the fastest (12.43%), trailed by water cooling (10.56%) and LN₂ cooling (9.17%).
- (2) The impact crater parameters for granites are quantitatively examined by 3D reconstruction. With the ongoing elevation

of heating temperature, the penetration depth L , damage volume V , and damage area S of impact craters generated by the PDC cutter all exhibit continuous increases. According to the derived dynamic magnification effect equation of granite, the dynamic magnification factor of intrusion β_1 is proportional to the thermal shock damage D_T . By the joint effects of high temperature and rapid cooling, the PDC cutter–rock interaction force will decrease, and the drilling time will be prolonged.

- (3) The size of the fragments obtained during the impact of the PDC cutter on granite is statistically calculated. The average fragment size d_m for rock is nonlinearly reduced with the elevation in heating temperature. The granite fragment size at 600 °C is about 45% smaller than the room-temperature value, and the damage degree of the LN₂-cooled specimen will be greater. Based on the derived fractal dimension D calculation equation of granite, the D value progressively increases as the thermal shock damage D_T increases.
- (4) The energy conversion and rock-breaking efficiencies during the Bit-SHPB test are discussed. In the impact process, both absorbed energy and energy conversion efficiency of granite increase as the temperature rises, which means that the corresponding fragments are broken into smaller debris. According to the derived normalized rock-breaking specific energy equation of granite, the rock-breaking specific energy δ is gradually reduced as the thermal shock damage D_T increases, indicating that the problems drilling tools need to solve gradually shift from increasing ROP to improving cleaning efficiency.

CRedit authorship contribution statement

Hao-Yu Wang: Writing – original draft. **Yan Xi:** Writing – original draft, Funding acquisition. **Wei Lian:** Formal analysis. **Jun Li:** Supervision. **Hai-Long Jiang:** Investigation. **Yu-Mei Li:** Methodology.

Conflicts of interest

The authors declare no conflict of interest.

Acknowledgments

This research was financially supported by the National Natural Science Foundation of China (52374001), Chongqing Natural Science Foundation (CSTB2024NSCQ-MSX0882), Foundation of State Key Laboratory of Petroleum Resources and Engineering (PRE/open-2408).

Appendix A

In case the back rake angle of the PDC cutter exceeds 0°, the calculation of the rock theoretical impact area S_T is achievable by geometric analysis, as displayed in Fig. A. The area can be obtained by calculus.

When the PDC cutter contacts granite, the calculation can be carried out according to Fig. A. The yellow line in the figure is the graphic infinitesimal unit Δx . The integral length at a location x apart from the top circle center can be formulated as:

$$s = 2R \sqrt{1 - \frac{x^2}{(R/\sin\theta)^2}} \quad (\text{A-1})$$

According to the above formula, the theoretical impact area of rock can be expressed as:

$$S_T = \int_{x_0/\sin\theta}^R 2R \sqrt{1 - \frac{x^2}{(R/\sin\theta)^2}} dx \quad (\text{A-2})$$

Besides, there is a conversion correlation of the x_0 value with the penetration depth d as follows:

$$x_0 = R - \frac{d}{\cos\theta} \quad (\text{A-3})$$

Through integral transformations, the outcomes can be formulated as:

$$S_T = \frac{\pi R^2}{2\sin\theta} - \frac{R^2}{\sin\theta} \arcsin\left(\frac{x_0}{R}\right) - \frac{x_0}{\sin\theta} \sqrt{2Ry_0(1-y_0)} \quad (\text{A-4})$$

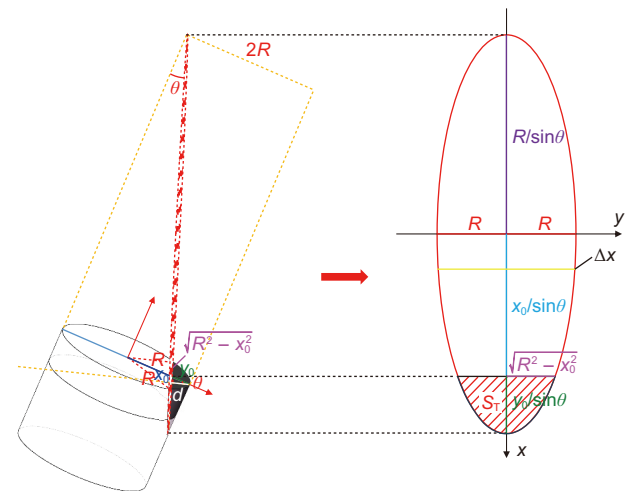


Fig. A. The calculation of the theoretical impact area S_T .

Appendix B

In case the back rake angle of the PDC cutter exceeds 0°, calculation of rock theoretical impact volume V_T is achievable by geometric analysis, as displayed in Fig. B. Clearly, the volume can be obtained by calculus.

- ① When the PDC cutter contacts granite, the penetration depth d is small, and the calculation diagram can be carried out according to Fig. B(a). The yellow line in the figure is the graphic infinitesimal unit Δx . The integral length at a location x apart from the top circle center can be formulated as:

$$s = 2\sqrt{R^2 - x^2} \quad (\text{B-1})$$

According to the geometric correlation, the corresponding integral height h at a location x apart from the center of the PDC cutter top surface can be formulated as:

$$h = (x - x_0) \cot\theta \quad (\text{B-2})$$

where θ signifies the back rake angle for the PDC cutter, x_0 denotes the distance from the top circle center to the edge when the PDC cutter penetrates the granite.

Besides, there is a conversion correlation of the x_0 value with the penetration depth d as follows:

$$x_0 = R - \frac{d}{\cos\theta} \quad (\text{B-3})$$

According to the above formula, the theoretical impact volume of rock can be expressed as:

$$V_{\text{Plastic}} = \int_{x_0}^R 2\sqrt{R^2 - x^2}(x - x_0)\cot\theta dx \quad (\text{B-4})$$

Through integral transformations, the outcomes can be formulated as:

$$V_{\text{Plastic}} = \frac{2}{3}(R^2 - x_0^2)^{\frac{3}{2}}\cot\theta + x_0 R^2 \cot\theta \arcsin \frac{x_0}{R} + x_0^2 \sqrt{R^2 - x_0^2} \cot\theta - \frac{\pi}{2} x_0 R^2 \cot\theta \quad (\text{B-5})$$

- ② When the PDC cutter penetration depth d increases continuously to reach the critical value, the calculation diagram can be carried out according to Fig. B(b). At this time, there is a conversion correlation of d with the PDC cutter height L as follows:

$$d = L \sin\theta \quad (\text{B-6})$$

According to the size of the PDC cutter, the penetration depth d at this time is 4.446 mm.

- ③ When the penetration depth d exceeds the critical value and continues to increase, the calculation diagram can be performed according to Fig. B(c). At this time, the value of the

impact volume is the difference between the two parts of the volume. The yellow and blue lines in the figure indicate the graphic infinitesimal units Δx and $\Delta x'$, respectively. The integral length at a location x apart from the top circle center can be obtained by Eq. (B-1). Similarly, the integral length s' at x' from the bottom circle center can be formulated as shown below:

$$s' = 2\sqrt{R^2 - x'^2} \quad (\text{B-7})$$

Meanwhile, the corresponding integral height h at a location x apart from the center of the PDC cutter top surface can be calculated according to Eq. (B-2). The integral height h' at the distance x' from the center of the bottom surface can be calculated according to the geometric relationship as follows:

$$h' = (x' - x_1)\cot\theta \quad (\text{B-8})$$

where θ is the back rake angle of the PDC cutter. x_1 is the distance between the center of the bottom circle and the edge when the PDC cutter penetrates the rock.

Moreover, there is a conversion relationship between the value of x_1 and the value of d as follows:

$$x_1 = R - \frac{d}{\cos\theta} + L \tan\theta \quad (\text{B-9})$$

According to the above formula, the theoretical impact volume of rock can be expressed as:

$$V_{\text{Plastic}} = \int_{x_0}^R 2\sqrt{R^2 - x^2}(x - x_0)\cot\theta dx - \int_{x_1}^R 2\sqrt{R^2 - x'^2}(x' - x_1)\cot\theta dx' \quad (\text{B-10})$$

Through integral transformations, the final results can be formulated as:

$$V_{\text{Plastic}} = \frac{2}{3}(R^2 - x_0^2)^{\frac{3}{2}}\cot\theta + x_0 R^2 \cot\theta \arcsin \frac{x_0}{R} + x_0^2 \sqrt{R^2 - x_0^2} \cot\theta - \frac{\pi}{2} x_0 R^2 \cot\theta - \frac{2}{3}(R^2 - x_1^2)^{\frac{3}{2}}\cot\theta - x_1 R^2 \cot\theta \arcsin \frac{x_1}{R} - x_1^2 \sqrt{R^2 - x_1^2} \cot\theta + \frac{\pi}{2} x_1 R^2 \cot\theta \quad (\text{B-11})$$

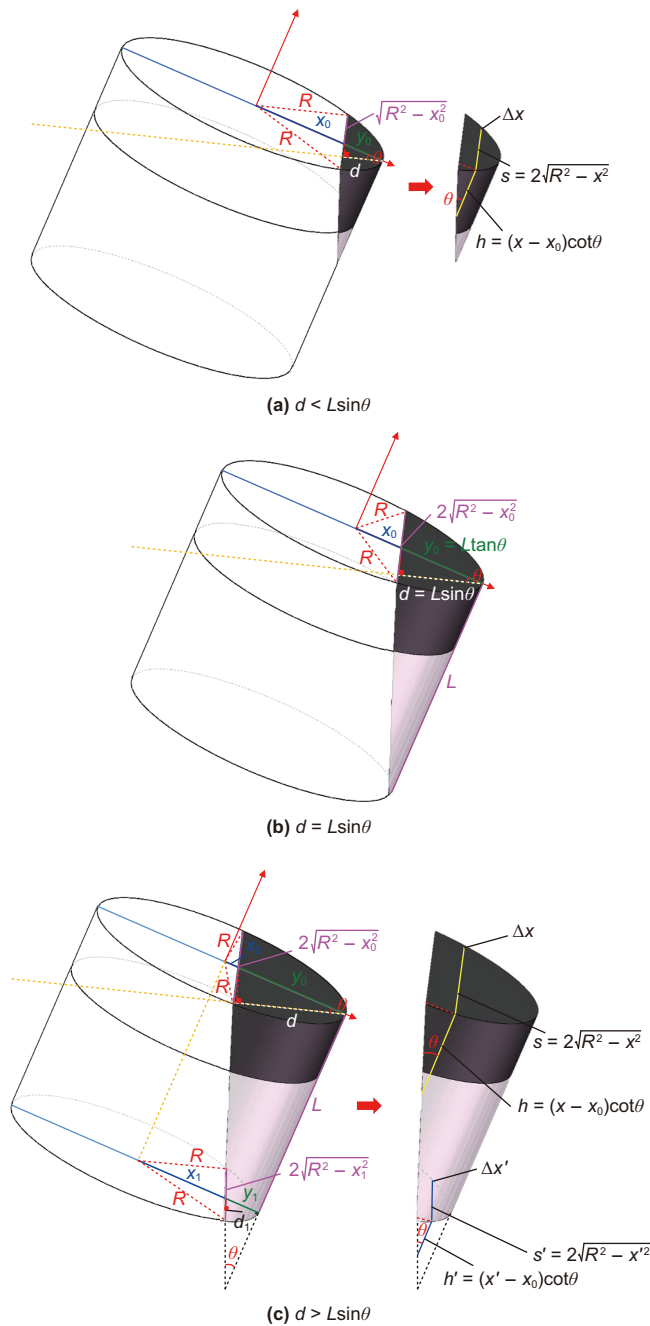


Fig. B. The calculation of the theoretical impact volume V_T .

References

- Breede, K., Dzebisashvili, K., Liu, X.L., et al., 2013. A systematic review of enhanced (or engineered) geothermal systems: past, present and future. *Geotherm. Energy* 1, 4. <https://doi.org/10.1186/2195-9706-1-4>.
- Brodsky, E.E., Lajoie, L.J., 2013. Anthropogenic seismicity rates and operational parameters at the Salton Sea geothermal field. *Science* 341, 543–546. <https://doi.org/10.1126/science.1239213>.
- Chen, P., Miska, S., Yu, M., et al., 2021. Modeling of cutting rock: from PDC cutter to PDC bit—modeling of PDC cutter. *SPE J.* 26 (6), 3444–3464. <https://doi.org/10.2118/206725-PA>.
- Cowie, S., Walton, G., 2018. The effect of mineralogical parameters on the mechanical properties of granitic rocks. *Eng. Geol.* 240, 204–225. <https://doi.org/10.1016/j.enggeo.2018.04.021>.
- Dai, F., Huang, S., Xia, K.W., et al., 2010. Some fundamental issues in dynamic compression and tension tests of rocks using split Hopkinson pressure bar. *Rock Mech. Rock Eng.* 43 (6), 657–666. <https://doi.org/10.1007/s00603-010-0091-8>.

- Dai, F., Xu, Y., Zhao, T., et al., 2016. Loading-rate-dependent progressive fracturing of cracked chevron notched Brazilian disc specimens in split Hopkinson pressure bar tests. *Int. J. Rock Mech. Min.* 88 (2), 49–60. <https://doi.org/10.1016/j.ijrmms.2016.07.003>.
- Dai, X.W., Huang, Z.W., Shi, H.Z., et al., 2021. Cutting force as an index to identify the ductile-brittle failure modes in rock cutting. *Int. J. Rock Mech. Min.* 146 (2), 104834. <https://doi.org/10.1016/j.ijrmms.2021.104834>.
- Dai, X.W., Huang, Z.W., Shi, H.Z., et al., 2022. Experimental investigation on the PDC cutter penetration efficiency in high-temperature granite. *Geothermics* 98 (7), 102281. <https://doi.org/10.1016/j.geothermics.2021.102281>.
- Dai, X.W., Chen, P.J., Huang, T., et al., 2023. Study on combined cutting and penetration of shaped PDC cutter under bottomhole condition. *Geoenergy Sci. Eng.* 229 (6), 102124. <https://doi.org/10.1016/j.geoen.2023.212124>.
- Fan, L.F., Wu, Z.J., Wan, Z., et al., 2017. Experimental investigation of thermal effects on dynamic behavior of granite. *Appl. Therm. Eng.* 125, 94–103. <https://doi.org/10.1016/j.applthermaleng.2017.07.007>.
- Fan, L.F., Gao, J.W., Wu, Z.J., et al., 2018. An investigation of thermal effects on micro-properties of granite by X-ray CT technique. *Appl. Therm. Eng.* 140, 505–519. <https://doi.org/10.1016/j.applthermaleng.2018.05.074>.
- Fan, L.F., Li, H., Xi, Y., 2022. Investigation of three different cooling treatments on dynamic mechanical properties and fragmentation characteristics of granite subjected to thermal cycling. *Undergr. Space* 7, 847–861. <https://doi.org/10.1016/j.undsp.2021.12.010>.
- Han, Y.N., Li, X.R., Feng, Y.C., 2020. A new approach to evaluate rock drillability of polycrystalline diamond compact bits using scratch test data. *Energy Explor. Exploit.* 38 (3), 1–21. <https://doi.org/10.1177/0144598719901091>.
- Han, Z.Y., Li, D.Y., Li, X.B., 2022. Dynamic mechanical properties and wave propagation of composite rock-mortar specimens based on SHPB tests. *Int. J. Min. Sci. Technol.* 32 (1), 793–806. <https://doi.org/10.1016/j.ijmst.2022.05.008>.
- Hu, H.G., Guan, Z.C., Zhang, B., et al., 2021. Structure design of weight-on-bit self-adjusting PDC bit based on stress field analysis and experiment evaluation. *J. Petrol. Sci. Eng.* 196 (2), 107692. <https://doi.org/10.1016/j.petrol.2020.107692>.
- Hu, J.J., Xie, H.P., Gao, M.Z., et al., 2022. Damage mechanism and heat transfer characteristics of limestone after thermal shock cycle treatments based on geothermal development. *Int. J. Rock Mech. Min.* 160 (5), 105269. <https://doi.org/10.1016/j.ijrmms.2022.105269>.
- Huang, K.L., Yang, Y.X., Liu, Y., et al., 2020. Study on rock breaking mechanism of PDC bit with rotating module. *J. Petrol. Sci. Eng.* 192, 107312. <https://doi.org/10.1016/j.petrol.2020.107312>.
- Ji, Z.S., Jiang, J.B., Shi, H.Z., et al., 2023. Experimental studies on rock failure mechanisms under impact load by single polycrystalline diamond compact cutter. *Pet. Sci.* 20 (2), 3100–3109. <https://doi.org/10.1016/j.petsci.2023.04.008>.
- Li, X.B., Lok, T.S., Zhao, J., 2005. Dynamic characteristics of granite subjected to intermediate loading rate. *Rock Mech. Rock Eng.* 38 (1), 21–39. <https://doi.org/10.1007/s00603-004-0030-7>.
- Li, X.W., Lin, J., Shao, W.H., et al., 2024. Study on the evolution law of physical mechanics and abrasion characteristics of granite under high temperature-water cooling treatment. *Case Stud. Therm. Eng.* 58, 104384. <https://doi.org/10.1016/j.csite.2024.104384>.
- Li, Y., Yu, W.J., Sun, H.X., et al., 2025. Effect of strain rate on the dynamic splitting behavior and fracture surface morphology of granite subjected to high-temperature treatment. *J. Mater. Res. Technol.* 39, 7231–7247. <https://doi.org/10.1016/j.jmrt.2025.11.052>.
- Li, Y.L., Peng, J.M., Zhang, L., et al., 2022. Quantitative evaluation of impact cracks near the borehole based on 2D image analysis and fractal theory. *Geothermics* 100, 102335. <https://doi.org/10.1016/j.geothermics.2021.102335>.
- Li, Y.L., Peng, J.M., Li, K.K., et al., 2021. An abrasive water jet assisted back reaming technique based on percussion drilling for reducing non-production time in geothermal energy development. *Geothermics* 89, 1201967. <https://doi.org/10.1016/j.geothermics.2020.101967>.
- Liu, S.B., Ni, H.J., Zhang, H., et al., 2021. Numerical study on optimal impact angle of a single PDC cutter in impact rock cutting. *Energy Rep.* 7 (5), 4172–4183. <https://doi.org/10.1016/j.egy.2021.06.076>.
- Liu, Y.L., Zhang, Y.J., Cheng, Y.X., et al., 2025. Experimental investigation on non-linear flow and convective heat transfer of damaged multi-fractured rock. *Appl. Therm. Eng.* 264, 125466. <https://doi.org/10.1016/j.applthermaleng.2025.125466>.
- Lou, C.D., Xie, H.P., Zhang, R., et al., 2024. Dynamic mechanical characteristics of deep Jinping marble in complex stress environments. *J. Rock Mech. Geotech.* 16 (2), 630–644. <https://doi.org/10.1016/j.jrmge.2023.08.005>.
- Ma, Y.C., Xie, X.F., Rong, Z., et al., 2023. Study on dynamic wear law of PDC bit under temperature effect. *Geoenergy Sci. Eng.* 230 (1), 212237. <https://doi.org/10.1016/j.geoen.2023.212237>.
- Mao, S., Shi, X.C., Meng, Y.F., et al., 2018. Experimental investigation of rock drillability for three rock types under varying wellbore pressure conditions. *Rock Mech. Rock Eng.* 51 (3), 2439–2445. <https://doi.org/10.1007/s00603-018-1472-7>.
- Niu, Q.H., Zhao, X.Y., Chang, J.F., et al., 2025. Numerical simulation on physical composite stimulation and geothermal development performance of hot dry rock: A case study from Matouying Uplift, China. *Appl. Therm. Eng.* 267 (3), 125714. <https://doi.org/10.1016/j.applthermaleng.2025.125714>.
- Peng, Y., Wu, H., Fang, Q., et al., 2018. Geometrical scaling effect for penetration depth of hard projectiles into concrete targets. *Int. J. Impact Eng.* 120, 46–59. <https://doi.org/10.1016/j.ijimpeng.2018.05.010>.
- Qiu, Y.F., Wu, J.W., Yang, Z.Y., et al., 2024. Experimental research on deformation response of hot dry rock (HDR) geothermal reservoir during hydraulic

- modification at 300 °C and depth 2500 m. *Energy* 312, 133610. <https://doi.org/10.1016/j.energy.2024.133610>.
- Rossi, E., Jamali, S., Saar, M.O., et al., 2020. Field test of a combined thermo-mechanical drilling technology. Mode I: thermal spallation drilling. *J. Petrol. Sci. Eng.* 190 (4), 107005. <https://doi.org/10.1016/j.petrol.2020.107005>.
- Shao, Z.L., Wang, Y., Tang, X.H., 2020. The influences of heating and uniaxial loading on granite subjected to liquid nitrogen cooling. *Eng. Geol.* 271, 105614. <https://doi.org/10.1016/j.enggeo.2020.105614>.
- Shi, H.Z., He, S.L., Xiong, C., et al., 2025. Development and application of a hybrid PDC bit for drilling the high temperature granite formation in the deep geothermal exploration well Fushenre-1. *Energy Geoscience* 7 (3), 100467. <https://doi.org/10.1016/j.engeos.2025.100467>.
- Song, H.Y., Shi, H.Z., Chen, Z.L., et al., 2021. Numerical study on impact energy transfer and rock damage mechanism in percussive drilling based on high temperature hard rocks. *Geothermics* 96 (3), 102215. <https://doi.org/10.1016/j.geothermics.2021.102215>.
- Song, H.Y., Shi, H.Z., Yuan, G.J., et al., 2022. Experimental study of the energy transfer efficiency and rock fragmentation characteristics in percussive drilling. *Geothermics* 105 (2), 102497. <https://doi.org/10.1016/j.geothermics.2022.102497>.
- Song, X.Z., Li, G.S., Huang, Z.W., et al., 2023. Review of high-temperature geothermal drilling and exploitation technologies. *Gondwana Res.* 122, 315–330. <https://doi.org/10.1016/j.gr.2022.10.013>.
- Song, D.D., He, M.M., Wang, J., et al., 2024. An experimental study of the effect of temperature on teeth breaking efficiency based on rock mechanical properties. *Nat. Gas Ind. B* 11 (3), 543–552. <https://doi.org/10.1016/j.ngib.2024.09.009>.
- SYT5426–2016, 2016. *Rock drillability measurement and its classification*. State Bureau of Petroleum and Chemical Industry.
- Wang, J., Dai, F., Zhou, L., et al., 2025. Thermomechanical properties and fracture behavior of dry-hot granite subjected to cyclic thermal shock and dynamic tensile loading. *Int. J. Rock Mech. Min.* 192, 106165. <https://doi.org/10.1016/j.ijrmms.2025.106165>.
- Wei, H.Z., Ma, L.J., Wu, J.W., et al., 2022. Dynamic mechanical behavior of coral rock subjected to high strain rate loading. *Mar. Geophys. Res.* 43 (3), 30. <https://doi.org/10.1007/s11001-022-09493-x>.
- Wu, X.G., Huang, Z.W., Li, G.S., et al., 2018. Experiment on coal breaking with cryogenic nitrogen jet. *J. Petrol. Sci. Eng.* 169, 405–415. <https://doi.org/10.1016/j.petrol.2018.05.061>.
- Wu, X.G., Huang, Z.W., Song, H.Y., et al., 2019a. Variations of physical and mechanical properties of heated granite after rapid cooling with liquid nitrogen. *Rock Mech. Rock Eng.* 52 (7), 2123–2139. <https://doi.org/10.1007/s00603-018-1727-3>.
- Wu, X.G., Huang, Z.W., Cheng, Z., et al., 2019b. Effects of cyclic heating and LN₂-cooling on the physical and mechanical properties of granite. *Appl. Therm. Eng.* 156, 99–110. <https://doi.org/10.1016/j.applthermaleng.2019.04.046>.
- Xi, Y., Wang, H.Y., Jiang, J.W., et al., 2023a. Impacts of different cooling methods on the dynamic tensile properties of thermal-treated granite. *Int. J. Rock Mech. Min.* 169 (2), 105438. <https://doi.org/10.1016/j.ijrmms.2023.105438>.
- Xi, Y., Wang, H.Y., Zha, C.Q., et al., 2023b. Numerical simulation of rock-breaking and influence laws of dynamic load parameters during axial-torsional coupled impact drilling with a single PDC cutter. *Pet. Sci.* 20 (3), 1806–1827. <https://doi.org/10.1016/j.petsci.2023.01.009>.
- Xi, Y., Wang, H.Y., Zhang, H., et al., 2024. Effects of different bedding angles and impact angles on the dynamic tensile properties of thermal-treated shale after cooling treatment. *Rock Mech. Rock Eng.* 57 (10), 8457–8481. <https://doi.org/10.1007/s00603-024-03973-9>.
- Xi, Y., Wang, H.Y., Kang, J.F., et al., 2025. Energy conversion and failure mechanism of rocks with different lithologies by PDC irregular teeth during percussive drilling. *Geoenergy Sci. Eng.* 247, 213714. <https://doi.org/10.1016/j.geoen.2025.213714>.
- Xiao, D., Hu, Y.F., Wang, Y.Y., et al., 2022. Wellbore cooling and heat energy utilization method for deep shale gas horizontal well drilling. *Appl. Therm. Eng.* 213 (9), 118684. <https://doi.org/10.1016/j.applthermaleng.2022.118684>.
- Xiong, C., Huang, Z.W., Shi, H.Z., et al., 2023. Investigations on the stinger PDC cutter breaking granitoid under in-situ stress and hydrostatic pressure conditions. *Int. J. Rock Mech. Min.* 164, 105312. <https://doi.org/10.1016/j.petsci.2022.10.006>.
- Xue, Y., Wang, L.C., Liu, J., et al., 2024. Experimental study on the effect of heating and liquid nitrogen-cooling cyclic treatment on mechanical properties and fracturing characteristics of granite. *Int. J. Rock Mech. Min.* 176 (1), 105691. <https://doi.org/10.1016/j.ijrmms.2024.105691>.
- Yagiz, S., 2009. Assessment of brittleness using rock strength and density with punch penetration test. *Tunn. Undergr. Space Technol.* 24 (1), 66–74.
- Yang, F.J., Wang, G.L., Hu, D.W., et al., 2021. Calibrations of thermo-hydro-mechanical coupling parameters for heating and water-cooling treated granite. *Renew. Energy* 168 (31), 544–558. <https://doi.org/10.1016/j.renene.2020.12.042>.
- Yang, F.L., Liu, W.J., Zhu, X.H., et al., 2024. The rock-breaking mechanism of thermal spalling-assisted rock cutting by PDC cutter. *Rock Mech. Rock Eng.* 57 (2), 993–1012. <https://doi.org/10.1007/s00603-023-03603-w>.
- Yin, T.B., Li, Qiang, Li, X.B., 2019. Experimental investigation on mode I fracture characteristics of granite after cyclic heating and cooling treatments. *Eng. Fract. Mech.* 222, 106740. <https://doi.org/10.1016/j.engfracmech.2019.106740>.
- Yin, T.B., Ma, J.X., Wu, Y., et al., 2022. Effect of high temperature on the brittleness index of granite, an experimental investigation. *Bull. Eng. Geol. Environ.* 81 (11), 476. <https://doi.org/10.1007/s10064-022-02953-z>.
- Zhang, W.Q., Sun, Q., Hao, S.Q., et al., 2016. Experimental study on the variation of physical and mechanical properties of rock after high temperature treatment. *Appl. Therm. Eng.* 98, 1297–1304. <https://doi.org/10.1016/j.applthermaleng.2016.01.010>.
- Zhao, Z.Y., Xue, J.C., Jin, J.F., et al., 2023. Experimental research on the dynamic constraining characteristics and fractal properties of sandstone under impact loading. *Case Stud. Constr. Mater.* 18 (3), e02174. <https://doi.org/10.1016/j.cscm.2023.e02174>.
- Zhou, Y.X., Xia, K., Li, X.B., et al., 2012. Suggested methods for determining the dynamic strength parameters and mode-I fracture toughness of rock materials. *Int. J. Rock Mech. Min.* 49, 105–112.
- Zhu, X.H., Luo, Y.X., Liu, W.J., et al., 2022. Rock cutting mechanism of special-shaped PDC cutter in heterogeneous granite formation. *J. Petrol. Sci. Eng.* 210 (3), 110020. <https://doi.org/10.1016/j.petrol.2021.110020>.
- Zhu, X.H., Dan, Z.W., 2019. Numerical simulation of rock breaking by PDC bit in hot dry rocks. *Nat. Gas Ind. B* 6 (6), 619–628. <https://doi.org/10.1016/j.ngib.2019.04.007>.