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*Research Article*

# Study on the Effect of Negative Temperature Change on the Fracture Morphology of Granite under Impact

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SHPB test system was used to conduct dynamic impact experiments on frozen granite under different negative temperatures. The fracture surface of granite under impact load was found via scanning electron microscope (SEM). The micromorphological characteristics of rock fracture under negative temperature are analyzed to explore the influence of negative temperature on the rock fracture morphology, and a practicable explanation is given for the mechanical property changes of rock under different temperatures. Research results showed that low temperatures (<-20°C) caused "frostbite" in granite, leading to a sharp decrease in the rock dynamic mechanical strength under a high strain. Fracture morphology analysis indicated that the lower negative temperatures resulted in the formation of cracks among the mineral particles in the granite. These cracks have poor plastic deformation ability and are easy to destabilize and expand under a high strain rate. Moreover, the coupling effect of impact and negative temperature will cause the cleavage of some crystalline minerals, eventually resulting in the low-stress brittle failure of granite. It is considered that the nucleation of cracks in negative temperature rock under impact load is mainly caused by crystal deformation, which can be divided into three types: the nucleation of cracks resulted from elastic incompatibility between the grains, the nucleation of cracks caused by interface slip, and the nucleation of cracks caused by plastic deformation in crystalline solid.

## 1. Introduction

Rock is essentially a porous medium, a multiphase body composed of solid mineral particles, pores between solid particles, and pore fluid [1]. The existence of pores and the composition of pore fluid have a vital influence on rock properties. When the porous medium of rock is in a negative temperature environment, the pore or fissure water inside the rock will undergo phase transformation and freeze. As a result, the rock mechanical and physical performances are not only related to its physical structure but also affected by water, temperature, and stress state [2]. Rock subjected to negative temperature will produce high tensile stress through a contraction as initial flaws in the rock, joints, and fissures will expand due to uneven contraction between particles. Tensile stress is caused by temperature stress in the rock, and pore or fissure water in rock undergoes a phase transformation from liquid water to solid ice at low temperatures [3–6]. The expansion of volume results in frost heaving which intensifies the development of cracks. However, the formation of ice has a certain freezing and filling effect on the defects such as pore cracks, which makes the multiphase rock more like a rock matrix and strengthens the basic mechanical properties of rock. As a result, how rock properties change under negative temperature is a problem that needs to be researched further.

Fractography is a science that studies the fracture of materials and it was first applied to the study of metal fracture [7]. In the past two decades, fracture topography has been gradually introduced into the field of rock mechanics. By observing and measuring the surface topography of rock fracture, the microstructure and crack propagation mechanism of rock are analyzed, and the damage and fracture properties and failure laws are revealed. However, most of the relevant researches are concentrated in the field of rock statics, and there are few researches on rock dynamics, especially those on the analysis of dynamic mechanical properties of frozen rock based on fracture morphology. Therefore, some strange phenomena of rock mechanical properties under impact and negative temperature coupling, such as strength deterioration of frozen rock at lower negative temperatures, are not well understood. In this paper, the fracture morphology of frozen granite under impact load was observed by SEM, a large number of unique fracture morphologies of the frozen granite caused by impact are captured. The micromorphological characteristics of rock fracture under negative temperature are used to analyze the influence of negative temperature against the rock fracture morphology, and a logical explanation is given for the change of mechanical properties of rock under different temperatures through the fracture morphology characteristics. At the same time, based on the characteristics of fracture morphology, the formation mechanisms of microcracks in frozen rock are summarized, and the influence of negative and freezing brittleness on the dynamic properties of frozen rock is explained.

## 2. Dynamic Impact Test and SEM-SCAN

*2.1. Dynamic Impact Test.* Granite blocks with good integrity and homogeneity were selected from Fangshan quarry as research materials. According to the SHPB test system requirements [8, 9], the rock block was cored, cut, and polished into $\Phi 74 \times 37$ mm cylindrical specimens. The nonparallelism of the axial direction and end face of specimen shall be controlled within 0.02 mm [10–13] as shown in Figure 1.

The dynamic impact test was implemented using a SHPB compression bar test device (with a large diameter of 75 mm) (as illustrated in Figure 2), the research material was water-saturated granite that had been frozen under various negative temperature conditions. Seven temperature grades were set up in the test, namely, -5°C, -10°C, -15°C, -20°C, -30°C, -40°C, and 25°C. The system of SHPB pressure bar test was added with temperature compensation device to ensure a constant negative condition during testing, and the effect of the fluctuation of room temperature against the test was weakened by preset negative temperature.

*2.2. Macroscopic Failure Characteristics.* Figure 3 reveals the macroscopic failure pattern of granite under strong impact at different temperatures. Here, granite frozen at different temperatures is destroyed under impact except at -10°C; however, there were evident differences in mass and shape of the fracture body.

(1) Under the effect of compressive stress wave, the sample was subjected to a strong axial compression at 25°C. The rock radially expanded and local failure occurred. The local fracture occurred between the lamellar and columnar splitting structure caused by tension

(2) At -5°C, rock brittleness is enhanced and deformation resistance declines at negative temperature. Under an effect of the compressive stress wave, the specimen is easy to form columnar splitting structure along the axial direction, and the fracture angle is about 110°, which is a typical tensile fracture

Figure 1: Part of rock specimens prepared.

Figure 2: SHPB experimental system.

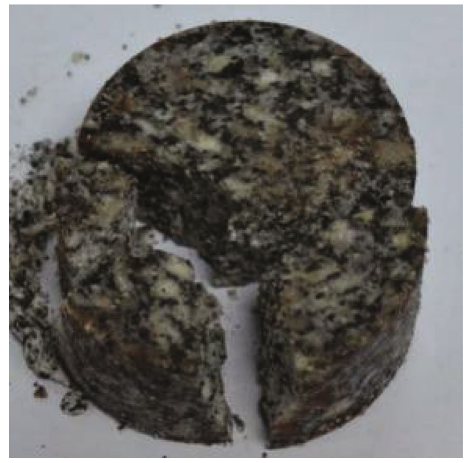
(3) At -10°C, at negative temperatures, the rock shrinks, and its resistance to radial expansion deformation increases. Under impact, the granite remains intact, and some specimens have tiny cracks

(4) At -15°C, the negative temperature further decreases, and the rock's resistance to radial shrinkage deformation begins to decline. Under the action of reverse tensile wave (which causes the radial rebound of the rock specimen), the lamination failure occurs

(5) From -20°C to -40°C, brittleness enhancement leads to a continuous decrease of rock resistance to deformation. Also, lower negative temperature results in the intersection together with initiation of a great deal of microcracks in the rock. Under the joint action of the two, rock specimens are destroyed and numerous cylindrical splitting architectures are generated, which are mainly formed by the unstable intersection and expansion of numerous cracks

The tensile failure of granite under impact is obvious. However, in addition to the intact granite at -10°C, the broken body formed by shear failure gradually appears with the decrease of negative temperature, which is particularly obvious at -30°C and -40°C. Combined with the analysis of fracture morphology, it can be inferred that the granite tends to shrink when it is subjected to negative temperature at -5°C and -10°C, and its impact resistance is improved, and the cleavage damage caused by tensile action is mostly presented

(a)



(b)

(c)

(d)

(e)

(f)

Figure 3: Continued.

(g)

Figure 3: Impact failure pattern of granite: (a) 25°C; (b) -5°C; (c) -10°C; (d) -15°C; (e) -20°C; (f) -30°C; and (g) -40°C.

Figure 4: JSM-5410 V Scanning Electron Microscopy (SEM).

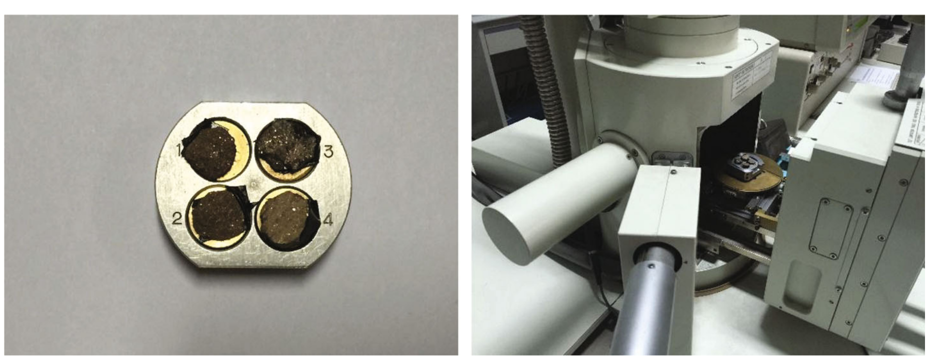
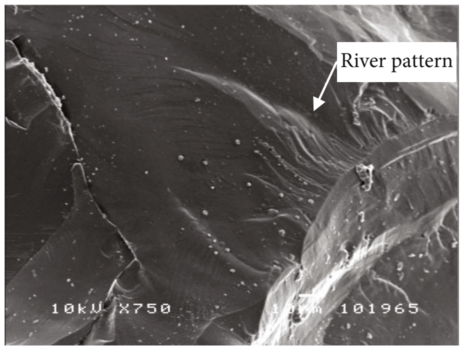


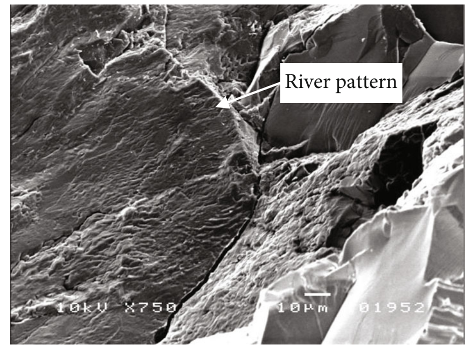

Figure 5: The specimen after gold plating.

under impact action. However, when the temperature drops to -30°C and -40°C, the fracture morphology of granite tends to be diversified, including cleavage fracture, shear fracture, and slip fracture. Therefore, the quasicleavage fracture formed under the mixed action of tension and shear plays a dominant role on the mesoscopic level.

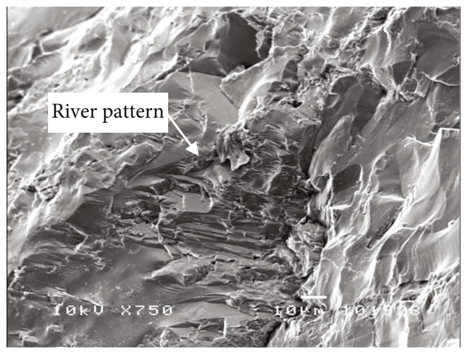
*2.3. SEM-SCAN.* The JSM-5410 V scanning electron microscope (SEM) of the State Key Laboratory of Coal Resources and Safe Mining of China University of Mining and Technology (Beijing) was used in this test, as shown in Figure 4. A scanning electron microscope can be roughly divided into a mirror body, electron optical system, power circuit control system, and cooling system. The mirror body consists of an electron optical system, a sample chamber, a detector, and a vacuum extraction system. The electronic optical system is composed of scanning coil, electromagnetic lens, electron gun, and so on. The power supply circuit system is composed of a power supply, signal processing, image display, and recording system for controlling the mirror body part and




(a) -40°C, ×750

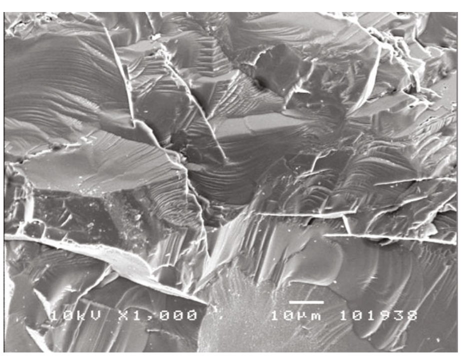



(b) 25°C, ×750



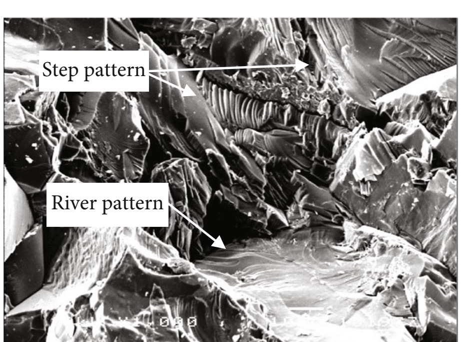

(c) 25°C, ×750

Figure 6: River Pattern.




25°C, ×1000

Figure 7: Curved facet and river pattern.




−40°C, ×1000

Figure 8: Step pattern.

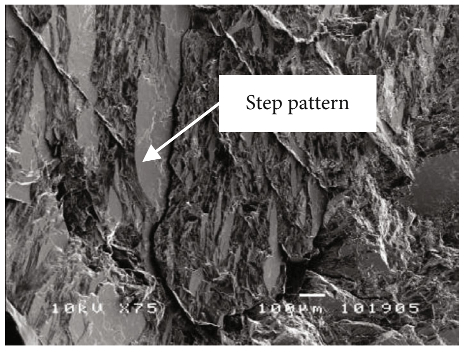
operation panel for all electrical parts. The vacuum system consists of a rotary mechanical pump (RP) for low vacuum pumping and an oil diffusion pump (DP) for high vacuum pumping.

This SEM scanning's observation material is granitic samples after a dynamic impact test. At various temperatures, SEM scanning specimens were prepared from impact broken bodies at 25°C, -5°C, -10°C, -20°C, -30°C, and -40°C, respectively. The diameter of the prepared specimen is no more than 10 mm and the height is no more than 2 mm, as shown in Figure 5. After specimen preparation, its surface is cleaned with alcohol and gilded after drying to improve the thermal conductivity of the specimen.

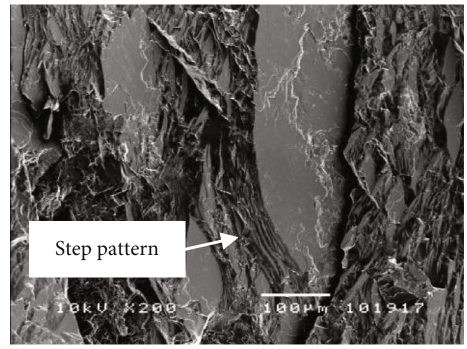
## 3. Fracture Morphology of Granite under Impact Load

In the macrosense, the rock is a type of brittle material, and its fracture has evident features of brittle failure. Nonetheless, in the broad sense, even brittle material may still have local plastic deformation in the fracture process. In accordance with the morphology of microfracture, the rock fracture in this section is divided into quasicleavage fracture and ductile fracture, as well as brittle fracture.

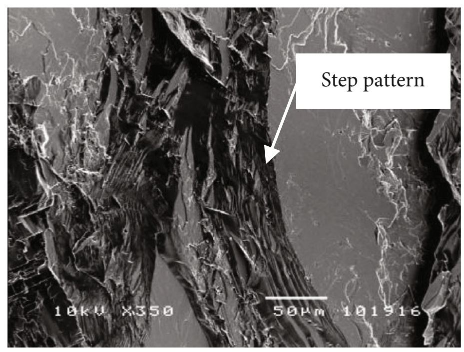
*3.1. Brittle Fracture.* Brittle fracture exhibits the rock characteristics of brittle failure. Under an action of impact, the rock fracture forms are principally intergranular fracture and transgranular fracture. According to the fracture form, it can be divided into intergranular fracture and cleavage




(a) -5°C, ×75




(b) -5°C, ×200




(c) -5°C, ×350

Figure 9: A series of steps on a cleavage plane of mica.

fracture. Nevertheless, on account of the lattice defects of the rock crystals and the variation of mesomorphology in the course of failure, many mesomorphological characteristics for instance step type and river type will occur at the fracture.

*3.1.1. River Pattern.* In the brittle materials, like rocks, river pattern is the most representative fracture characteristic. Its generation can be explained through the following facts: the material separates along the sequence of crystal planes with various heights rather than a certain crystal plane when there exist defects in the material crystal, resulting in a sequence of steps on the fracture surface. All steps have an identical style because they are subjected to nearly the same force. A series of closely spaced steps will merge layer by layer during the crystal separation and crack growth process, producing river pattern as illustrated in Figure 6.

Figure 7 shows that the surface of the fracture is covered with river patterns and overlapping morphologies of different scales. This is because the cleavage of a crystal can occur on multiple planes, and its fracture path is complex under the action of the stress field, causing the combination of multiple cleavage planes, and the series of cleavage steps formed constitute the complex morphology of fracture. The river pattern is composed of many cleavage surfaces with gradual refinement.

*3.1.2. Step Pattern.* For the step pattern, its mechanism is the same as river pattern; however, the cleavage surface of step type does not converge, as shown in Figure 8. Under an effect of impact load, the cleavage steps are arranged along crack propagation direction, which perpendicular to the surface of crack, and the needed free surface energy is small.

The cleavage plane of mica in granite is very smooth and flat, and its flat area extends to a larger area. Mica tends to split along multiple parallel cleavage planes under the impact, resulting in multiple steps on the cleavage plane (see Figure 9). The cleavage process is perfect and no deformation occurs during the cleavage.

*3.1.3. Dot Pattern.* When the cleavage plane of mica collides with other mineral particles during impact, crack propagation extends from the cleavage plane to the surface of the mineral particles. There are two modes of crack propagation, one is to advance through the highest point of eutectic, the other is to go around the two sides of mineral particles. The two kinds of cracks confluence and continue to expand and, finally, form a dot pattern on the cleavage plane. Figure 10 shows the dot pattern of the cleavage section of granite at -5°C.

*3.1.4. Fan-Shaped Pattern.* Fan-shaped pattern is also known as feather pattern. Cleavage cracks derived from the crystal propagate outward in a fan-shaped manner. As illustrated in Figure 11, the step pattern and river pattern can be considered fan bones that support the surface of fan.

*3.1.5. Wallner Line.* Wallner line is the micromorphology generated from the interaction between the spherical shock wave centered on defect and the front end of the crack propagation. It exhibits that in the phase of elastic deformation, the material is destroyed, plastic deformation does not exist

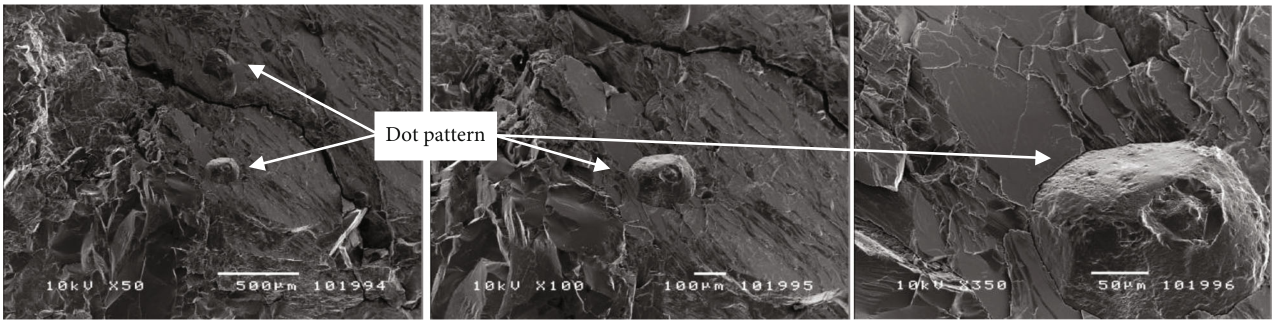
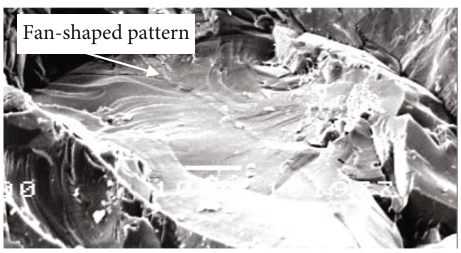
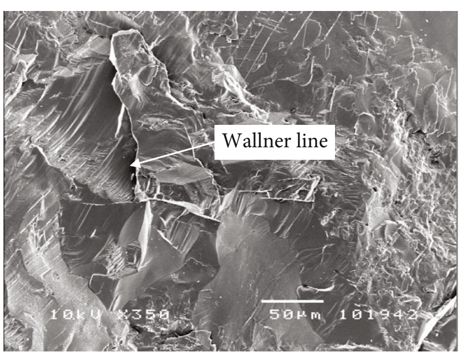



Figure 10: Dot pattern.




−40°C, ×1000

Figure 11: Fan-shaped pattern.




25°C, ×350

Figure 12: Wallner line.

in the whole process, and the separation mode is independent of the crystal architecture. When the temperature of brittle rock is low, the Wallner line fracture morphology will also occur. Figure 12 reflects the fracture morphology of the granite Wallner line.

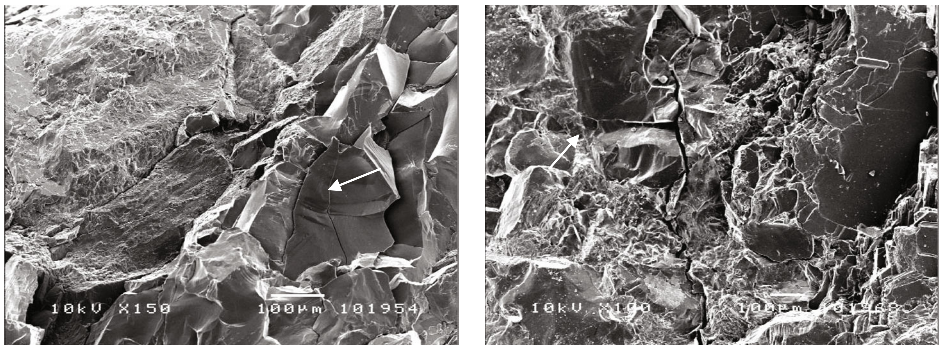
*3.1.6. Secondary Crack.* On the rock cleavage surface, the secondary crack is perpendicular to the propagation direction of the major crack. Figure 13 displays the secondary crack on the granite cleavage plane under an effect of impact load.

*3.1.7. Lamellar Tearing Fracture.* For the rock materials, lamellar tearing fracture is a classical transgranular fracture morphology under an effect of impact load. Feldspar and mica minerals in granite are rich in cleavage planes. Under the effect of impact load and low temperature, the initial cracks in rock can expand rapidly between layers. However, due to the low-temperature froze brittleness and anisotropy of rock materials, together with the effect of second phase materials, internal impurities and interlayer soft tissue, the secondary cracks are easy to appear in the course of crack propagation. As a result, the rock fracture at the layered architectural plane looks rough. It is found by SEM that the microstructure of the fracture here appears like lamellar tearing, so it is called lamellar tearing fracture. Figure 14 shows the lamellar tearing fracture of granite under impact.

*3.1.8. Intergranular Fracture.* In comparison with crystal cleavage fracture, the intergranular fracture is another microform of the brittle fracture, and its generation is closely associated with the material stress state. From microscopic morphology, intergranular fracture particles or crystals commonly keep intact and possess a strong sense of three-dimensional. Its shape is rock sugar pattern or polyhedron, and the crystal interface between the neighboring particles is smooth with no significant characteristic morphology, as reflected in Figure 15.

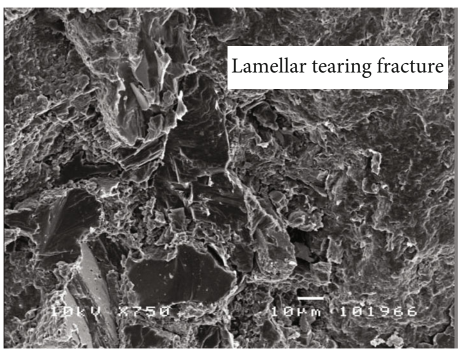
*3.2. Ductile Fracture.* Ductile fracture is defined as the process of local deformation in the course of crack propagation. When the crack propagates inside the material, the material without dislocation at the tip can be defined as the brittle material, but if the crack propagates at the tip with dislocation nucleation or dislocation source activation near the tip, the material is ductile material. It cannot be regarded as the brittle fracture when the material fracture is smooth relatively. Numerous fracture instances confirm that the plane fracture morphology is fully ductile at low observation times under high observation multiple, indicating that the fracture is ductile. Hence, there is no significant difference between brittle fracture and ductile fracture. In many conditions, the crack type requires to be identified through the observation scale of crack surface. Figures 16–19 display the rock ductile fracture morphology under the effect of impact load.

*3.2.1. Parallel Slip Line Pattern.* In the ductile fracture, slip separation is a prevalent fracture form. Under the effect of impact load, rock particles slide along separation surface and create lots of the linear traces on the surface of fracture. This evident slip separation texture can be locally found through SEM.



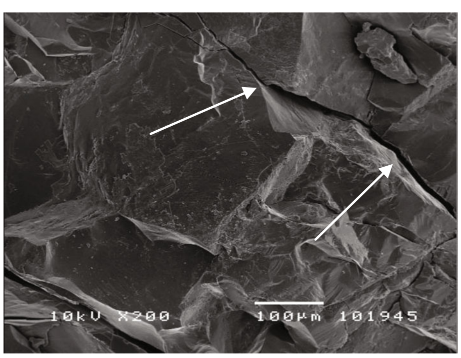

(a) 25°C, ×150 (b) -20°C, ×100

Figure 13: Secondary crack.




25°C, ×750

Figure 14: Lamellar tearing fracture.

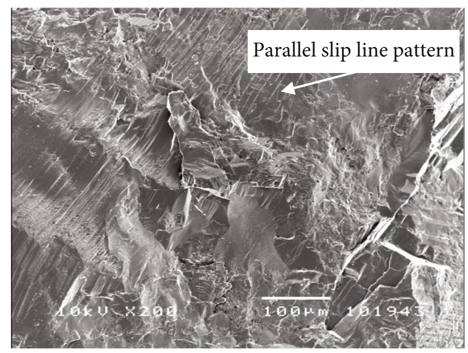



−30°C, ×200

Figure 15: Intergranular fracture.

*3.2.2. Stripe Pattern.* Under low magnification, a stripe pattern can be seen in some rock fractures as a series of linear parallel fringes. The cyclic times of stress waves propagating back and forth in the granite specimen are related to this fracture pattern.

*3.2.3. Shear Band Pattern.* The deformation of some granite regions is determined by the creation of highly localized strong shear stress zone in rock. Subsequently, the rock breaks and isolates in a direction parallel to shear stress zone. When the separation interface is observed at high multiples, there will be tearing ridges, thus forming shear band patterns.




25°C, ×200

Figure 16: Parallel slip line pattern.

*3.2.4. Arc Groove Pattern.* Dynamic stress balance is use in the process of the dynamic impact of granite specimen using SHPB test device, and its essence is to achieve the uniform force of the specimen as a whole through multiple reflections of stress waves in the specimen. The reflection of stress waves back and forth in the specimen will form an arc groove pattern on the fracture.

*3.3. Quasicleavage Fracture.* Quasicleavage is applied for the description of the brittle cleavage fracture of the multiphase materials that contains fine-scale polymerization. At present, it is employed to the fracture containing both ductile cleavage and crystal cleavage. It is also called transition fracture between ductile fracture and cleavage fracture. Quasicleavage fracture is smooth relatively macroscopically, but it has the feature texture of ductile fracture and the mesomorphology of the cleavage fracture simultaneously. As a result, quasicleavage fracture may exhibit various mesoforms, for example, tear ridges, rivers, steps, secondary cracks, slip lines, and stripes. Figure 20 reveals the mesomorphology of the quasicleavage fracture in three rocks under an effect of impact load.

## 4. The Influence of Freezing Temperature of Granite Fracture Morphology

Figure 21 shows the changes of fracture morphology of granite at different temperatures. The fracture morphology

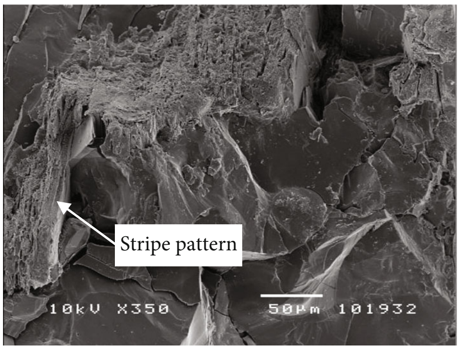



Figure 17: Stripe pattern (-30°C, ×350).

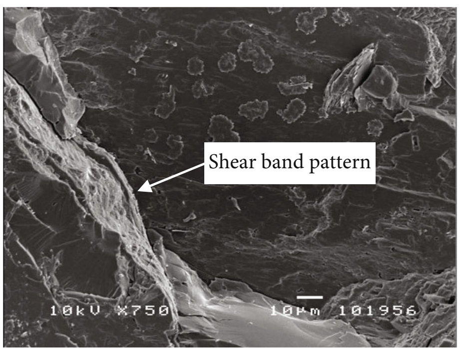



Figure 18: Shear band pattern (-30°C, ×750).

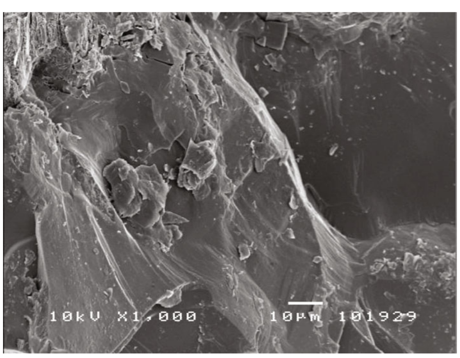



Figure 19: Arc groove pattern (-30°C, ×1000).

of granite at 25°C is complex, which includes river patterns formed by crystal cleavage, slip line patterns left by crystal slip on the section. Generally, the fracture morphology of granite at 25°C is diverse and slightly rough. When the temperature reduces and enters the negative temperature domain, the fracture of granite in the range of -5°C to -20°C is a mainly brittle fracture, and the river pattern and step cleavage increase gradually. The slip separation occurs in some areas due to shear deformation, and the shear band pattern and stripe pattern appear. After -20°C, the characteristics of rock slip separation caused by shear deformation become more obvious, and a large number of shear bands, slip lines, and flat surface patterns appear in the mesofracture morphology.

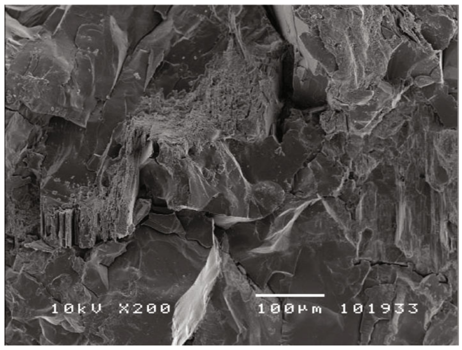
The negative temperature from -20°C to -40°C possesses an evident effect against the granite fracture morphology such that it exhibits certain frost brittleness at negative temperatures. Compared with 25°C, the proportion of step pattern and river pattern in fracture morphology increases at -20°C, whereas the slip line pattern also appears in large quantity. As the negative temperature continues to decline (-30°C to -40°C), the slip separation phenomenon increases, and a large number of shear band patterns and quasicleavage fractures appear on the section. At the same time, there are very obvious cracks, which are derived from secondary defects. The lower negative temperature will lead to the formation of secondary defects such as microcracks among the mineral particles in granite. These cracks have poor plastic deformation ability and are easy to destabilize and expand under high strain rate loading. Moreover, the coupling effect of impact and negative temperature will cause the cleavage of some crystalline minerals resulting in low-stress brittle failure occurrence along the fracture and cleavage plane of granite.

## 5. Discussion

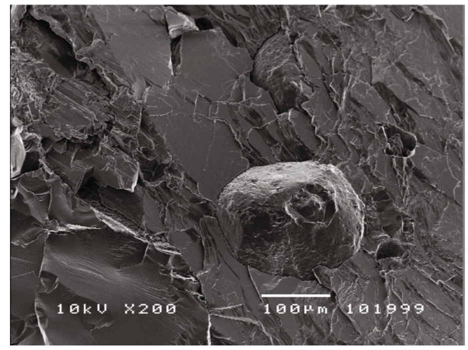
Fracture is the material's reaction to external load; it can also be caused by internal shrinkage, diffusion, and composition changes caused by temperature and chemical composition changes [14–16]. The cause of the crack is largely related microstructure of the material. The cause of the nucleation of the crack can be deduced and the nucleation point of the crack can be found by analyzing the microstructure of the material's fracture surface [7, 17]. By simulating and analyzing the fracture morphology of granite, it is preliminarily inferred that the nucleation of cracks in rocks at negative temperature is mainly caused by crystal deformation in rocks under impact load.

*5.1. Crack Nucleation Caused by Elastic Incompatibility between Grain.* Solids consist of particles or rigid phases, particularly rocks [18–20]. Since the elasticity of adjacent crystalline grains is not the same, stress will be generated under the action of external forces, and then, cracks will occur at the interface or inside the grains, as shown in Figures 22(a) and 22(b), respectively. On account of the differences in chemical composition, physical structure and crystal orientation between the grains, there are significant differences in their elastic modulus, which represents that externally imposed stress and internally generated stress will produce different elastic strains in the two grains, which may result in the local high stress and be released through the crack generation.

*5.2. Crack Nucleation Caused by Interface Slip.* There will be relative slip between the rigid crystals inside the rock as a result of external load, and dislocation will form between the two parts of the slip [21, 22]. Due to stress, the dislocation will gradually plug up and finally lead to the cracking of the end of grain boundary, as shown in Figure 22(b). If there are rigid particles and inclusions on the grain boundary, plastic holes will appear in the deformation process. Furthermore, when stress is applied steadily, plastic holes will continue to expand and aggregate and eventually nucleate on the grain boundary, and then, cracks may occur on the slip plane of the crystal.

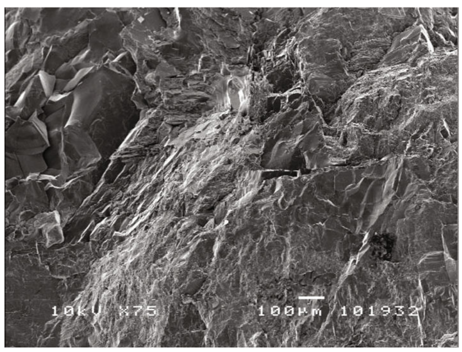



(a) -30°C, ×200

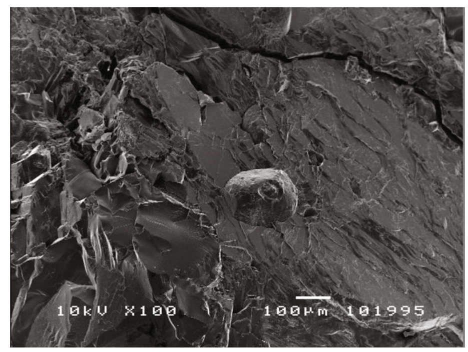



(b) -5°C, ×200

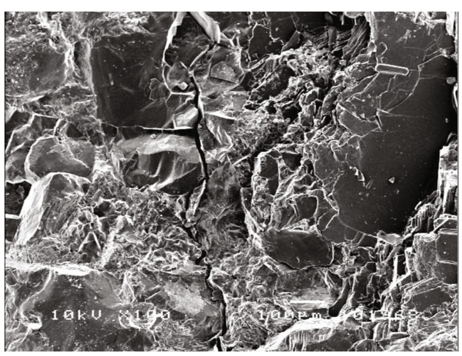
Figure 20: Quasicleavage fracture.



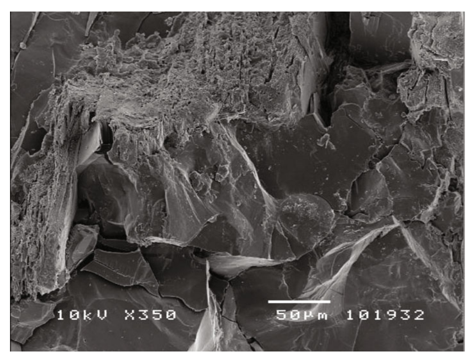

(a) 25°C, ×75



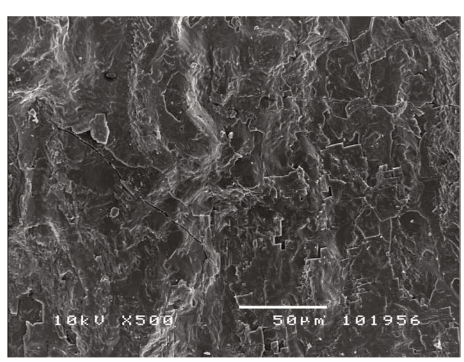

(b) -5°C, ×100



(c) -20°C, ×100

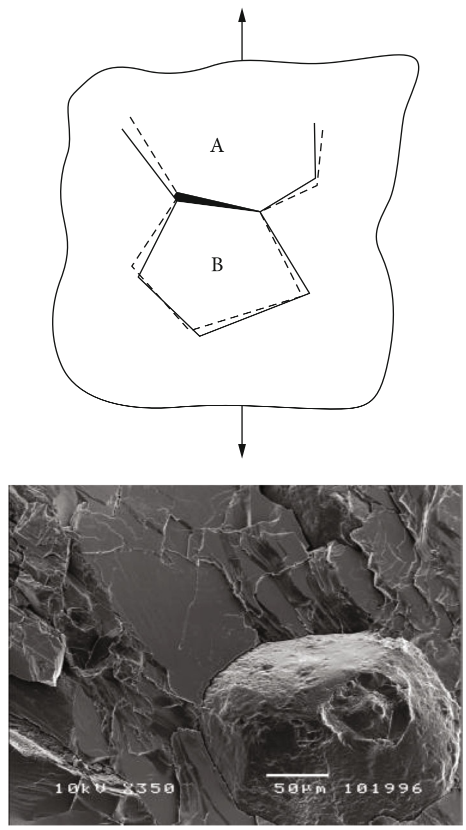



(d) -30°C, × 350

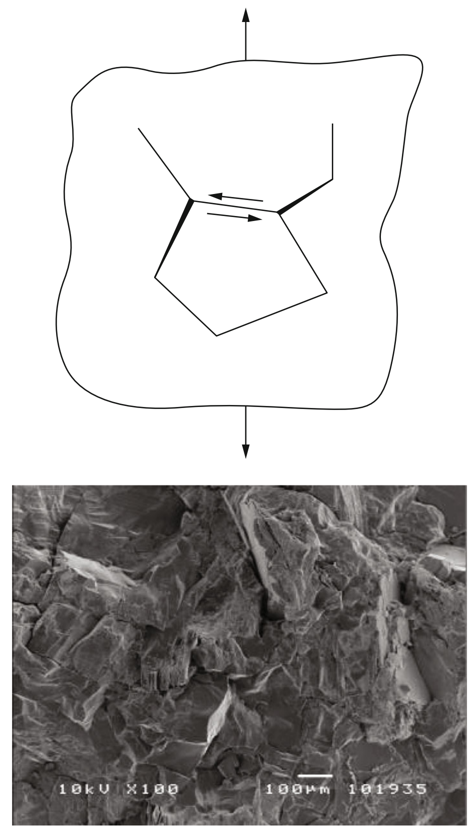



(e) -40°C, ×500

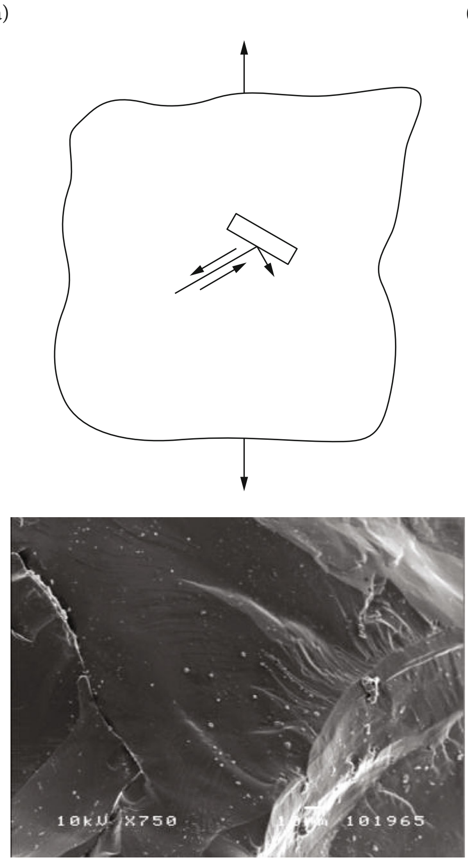
Figure 21: Fracture morphology of granite in different temperatures.




(a)




(b)




(c)

Figure 22: Example crack nucleation caused by deformation.

*5.3. Crack Nucleation Caused by Plastic Deformation in Crystalline Solids.* Since rock materials are prone to shear deformation at negative temperatures. Microscopic analysis revealed that shear deformation is resulted from the coordinated movement of numerous dislocations (local deformation twining) or sliding of single dislocation inside the crystal or grain. The acquiring shear stress is also confined to narrow band. Hence, when the shear band encounters obstacles, for instance second phase particles or grain boundaries, at the tip of the shear band, the high local stress will be formed, leading to crack nucleation [23, 24], as shown in Figure 22(c). In the process of crack nucleation, the crystal structure of the material and the direction of the applied stress determine the direction of shearing and the direction of the slip plane and twin plane. The plane of crack nucleation and the crystal structure of the material are closely associated with the intensity of barrier interface. The crack exhibited in Figure 22(c) appears in the shear band of the identical grain. Nonetheless, when the interface or barrier is weak or the energy needed for the propagation of crack is low, cracks will be generated at the interface or barrier on the weak surface of the material.

## 6. Conclusions

In this paper, the fracture morphology of frozen granite under an effect of impact load was observed by SEM. The micromorphological characteristics of rock fracture under negative temperature are extensively analyzed to explore the influence of negative temperature against the rock fracture morphology which indicated the following:

(1) The pattern of fracture surface changes regularly with temperatures, which reflect the change of impact fracture mechanism of frozen rock to a certain extent. From -5°C to -20°C, the granite is a mainly brittle fracture, and the fracture morphology is mainly stepped pattern and river pattern. Then after -20°C, the rock is prone to shear deformation under the impact and the shear band pattern, parallel slip line pattern, and flat plane pattern. This is because slip separation appears in large numbers. With the continuously reducing temperature, the phenomenon of crystal slip separation also increases, and a large number of shear band patterns appear on the fracture morphology

(2) The analysis of fracture morphology reflects that the lower negative temperature leads to the creation of cracks among the mineral particles in the granite. These cracks have poor plastic deformation ability and are easy to destabilize and expand under an action of high strain rate loading. Moreover, the coupling effect of impact and negative temperature will cause the cleavage of some crystalline minerals, eventually resulting in the low-stress brittle failure of granite

(3) In accordance with the analysis of rock fracture morphology, the nucleation of cracks in negative temperature rock under impact load is primarily caused by crystal deformation. Also based on different nucleation mechanisms, it can be divided into three types: the nucleation of cracks caused by crystalline grain mismatch, the nucleation of cracks caused by interface slip, and the nucleation of cracks caused by plastic deformation in crystalline solid

## Data Availability

The experimental data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors state that they have no conflict of interest. The funder has no role in the research design; in collecting, analyzing, or interpretating the data; when writing the manuscript and when deciding to publish the results.

## Authors' Contributions

Y.Y. was responsible for the conceptualization, methodology, validation, data curation, visualization, writing, and original draft preparation; Y.Y., N. Z, and J.W were responsible for the investigation; all authors were responsible for writing, reviewing, and editing; J. W, and Y.Y. were responsible for the supervision, project administration, and funding acquisition; all authors have read and agreed to the published version of the manuscript.

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