Research Article

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A modelling resin material and its application in rock-failure study: Samples with two 3D internal fracture surfaces

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Abstract: The mechanism of fracture propagation, interaction and coalescence inside rock masses is a highly concerned issue in geotechnical engineering. But as it is difficult to manufacture 3D internal pre-fractures and observe directly the failure evolution process inside real rocks or their opaque similar materials, most previous studies have been limited to 2D conditions. The experiment investigation on 3D rock failure is still in a preliminary stage. In this study, a resin material has been developed by extensive formula tries. It is absolutely transparent and the ratio of tension–compression strength (brittleness value) can be 1/6.6 at -10 to -15°C . It is much more brittle and rock-like than analogous materials used by former scholars. A set of preparation, casting mould, and post-processing technologies were established and specimen-making with multiple pre-fractures is enabled. In the designed scheme, specimens are made with two parallel internal fracture surfaces yet of four different stagger separations. Uniaxial tests were carried out and the stress–strain relationship is analysed. It is shown that the specimen has gone through four stages as the traditional rock test before failure. Many diverse forms of secondary fractures, such as wrapping wing crack, petaloid crack, and giant quasi-wrapping fracture surface, which were not found in 2D

conditions have appeared and their evolutions were clearly seen in each stage.

Keywords: rock failure, transparent and brittle material, specimen-making technology, internal pre-fractures, fracture propagation

1 Introduction

Rock mass is a well-known geological medium, which has experienced long tectonism. It is also a complicated material consisting of faults, fracture surfaces, fissures, etc. With external load, the fractures inside rock mass will propagate and interact, making a controlling effect on its macro deformation and failure. Thus, it is of significance for solid failure mechanism and earthquake research to investigate the fracture evolution of rocks containing pre-fractures under external force and the accompanying physical phenomena. In previous studies [1–9], various approaches have been applied to study the fracture evolution process and last failure forms of rocks, including rock sampling, model testing, geophysical detection (such as CT scanning, acoustic emission, and resistivity method), and numerical calculation (ABAQUS, UDEC, PFC, DDA, RFPA, etc.). But as it is of great complexity to prepare rocks with 3D pre-fractures and hard to observe opaque rock-like materials from the inside directly, reported test results on propagation and evolution of 3D fractures are still very few. CT scanning and acoustic emission are two essential methods that have been effectively used in monitoring internal fracture evolution of rocks and their opaque similar materials. But they do have drawbacks. To begin with, CT scanning is too expensive for common use. Acoustic emission will be inevitably interfered and thus inaccurate in fracture localization, especially for small-sized specimen and short rock bridges. Even so, they are still not straight forward enough. Moreover, the heterogeneity of rock cannot be neglected and always make the failure process irregular and uncertain. In previous studies,

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penetrated or surface pre-fractures were widely carved on a plane rock specimen. The evolution laws of a single or more fractures under uniaxial and biaxial loadings have been studied. Meaningful results were achieved [10–13]. Some preliminary test results have also been acquired on 3D fracture evolution. The basic failure characteristics of a single 3D fracture were described [14–19]. In recent years, more experiments and fundamental numerical simulations have been conducted. Multiple materials, such as rock, gypsum, ceramics, resin, and polymethyl methacrylate (PMMA), have been adopted to produce specimens with 3D pre-fractures. Basic understandings have been obtained regarding the influence of fracture orientation and depth on the propagation laws. But for all previous similar transparent materials (i.e. resin and PMMA), their brittleness (tension–compression strength ratio) actually cannot satisfy the brittle characteristics of real rocks. Specifically, the brittleness of resin material in [16] is $1/3$ at -17°C ; the PMMA in [17] also possesses a $1/3$ brittleness yet at a much lower temperature of -50°C ; the brittleness of resin material in [18] is $1/5$ at -20°C , but showing very poor transparency. In this study, a mixed resin material with the brittleness of $1/6.6$ at -10 to -15°C has been developed by extensive formula tries. It is much brittle than before and closer to real rocks in brittle properties, such as marble and sandstone. Its transparency is as well greatly enhanced and the full internal fracture evolution process can be clearly seen. This provides a good opportunity for further study on fracture evolution of real rocks. By adopting the new material, investigations on propagation mechanism and strength characteristics of specimens with multiple internal pre-fractures and their different arrangements are carried out. Besides, a set of preparation, casting mould, inner pre-fracture arrangement, and post-processing technologies were established. Some significant improvements have been made up for deficiencies of former experiments and great advances in this field, such as the vacuum treatment before pouring for specimen transparency, replacement of original metal pre-fracture by mica sheet, and demountable moulds, could be considered. Generally, this study is most likely to promote experiment research in geoscience and geotechnical engineering, together with the theoretical analysis and engineering application.

2 Material formulation of the pre-fractured specimen and test design

In this section, preparations of the new resin specimen containing two parallel internal fracture surfaces are illustrated. The test design scheme is presented.

2.1 Formulation of the transparent resin material

For those materials used to simulate pre-fractured rocks, their mechanical properties must be first close enough to those of rocks. Besides, it is essential that multiple independent fractures could be made inside the specimen. It is also required that the specimen possesses a big enough size in the case of boundary effect. Therefore, it makes a good choice for resin to be the material. Commonly, resin material stands for a category and is basically made up of resin, curing agent, and accelerant at a particular mixing ratio. Curing temperature and mixing ratio are two factors that matter most on the mechanical properties of the specimen after solidification.

In this study, comprehensive tries have been made on mechanical properties of resin material under different temperature and mixing ratio conditions. A modified resin material with good brittleness was eventually developed. It is much brittle than before and made up of C epoxy resin and related hardener. The 2D or 3D pre-fractures could be fabricated inside the specimen. Its ingredients are shown in Figure 1.

The C epoxy resin is a white transparent liquid with low viscosity at room temperature. It is odourless and harmless while the hardener gets a pungent smell; therefore, it is necessary to conduct specimen-making in a well-ventilated place. The mixture will solidify at room temperature showing high strength and behave stably both in physical and chemical characteristics. Particularly, its activity is adjustable by changing the proportion of hardener. During specimen-making, a particular mould is cast and a systematic treatment of baking, cooling, and vacuuming is requested. The completed specimen is totally transparent (as displayed in Figure 2) and has a $1/6.6$ brittleness at -10 to -15°C . Its mechanical parameters are shown in Table 1.

Figure 1: The resin material's mixing ingredients: C epoxy resin and hardener.

Figure 2: The eventually completed specimen.

Compared with some rocks regarding mechanical parameters, from Tables 1 and 2, it can be seen that the resin material is relatively similar to them. It is also worth mentioning that brittleness values of previous scholars are 1/3 at -17°C [16], 1/3 at -50°C [17], and 1/5 at -20°C [18], respectively. Therefore, it can better simulate certain kinds of rocks in brittle mechanical properties.

2.2 Specimen dimension, pre-fracture arrangements, and loading equipment

The specimen is a $140\text{ mm} \times 70\text{ mm} \times 50\text{ mm}$ block as shown in Figure 3 and big enough to keep off boundary effect. Both internal fracture surfaces are $18\text{ mm} \times 12\text{ mm}$ elliptic mica sheet. Compared with metal sheets adopted by previous studies as pre-fractures, mica sheet possesses exceedingly low stiffness and therefore will hardly influence the specimen's deformation during test. In this way, it can better simulate fractures and weak mechanical planes in real rocks. Besides, it is shaped during the solidification procedure by a specialized steel mould, as shown in Figure 4.

For the test design, there are four pre-fracture arrangement schemes in this study. As Figure 3 displays, vertical space a , the distance between two parallel fracture surfaces, is 12 mm and the stagger separation b (distance between projections of two pre-fractures' centroids when projected to

Table 2: Mechanical parameters of specified rocks [20]

Rock	Limestone	Marble	Gneiss	Quartzite
Compressive strength/MPa	76.9	101.6	114.8	172.0
Tensile strength/MPa	7.1	7.5	8.2	16.3

Figure 3: Specimen dimension and pre-fracture arrangement schemes. $a = 12\text{ mm}$; $b = 5, 12, 20, \text{ and } 30\text{ mm}$, respectively.

the same parallel line) is 5, 12, 20, and 30 mm, respectively. Both pre-fracture surfaces make a 45° inclined angle with the loading direction. Moreover, the arrangement of pre-fractures is required before resin pouring.

The mould consists of five perspex plates which have been glued together as a whole with insulative silicone grease (Figure 5). To get pre-fracture arrangements of different angles and types, pinholes are drilled on left and right perspex plates of the mould at any location optionally, then thread filaments through these pinholes and paste pre-fractures to them as planned. Overall, the mould can be utilized to prepare specimens with different numbers and relative positions of internal 3D fractures. The loading equipment is an mechanical testing and simulation (MTS) rock mechanical test system as shown in Figure 6. Besides, specimens must be kept in an icebox for 24 h at -20°C in

Table 1: New resin material's mechanical parameters

Elastic modulus/GPa	Density/g/cm ³	Compressive strength/MPa	Tensile strength/MPa	Poisson ratio	Cohesion/MPa	Friction angle/ $^{\circ}$
16	1.16	107.6	16.3	0.21	20.9	47.4

Figure 4: The steel mould for pre-fracture shaping.

Figure 5: The perspex mould for specimen-making.

advance before the test. Dry ice is placed around to retain a low temperature condition, and an infrared thermometer is employed to monitor the temperature change. The loading speed is 0.02 mm/s, and three linear variable differential transformer (LVDTs) are adopted to record axial and lateral deformations.

3 Test results and analysis

In this section, tests on the four cases of different stagger separations are illustrated. They are listed by an increasing stagger separation from 5 to 30 mm.

By using the aforementioned technologies in Section 2, specimen-making can be realized in a batch, almost without distinctions. Furthermore, to get excellent photographic effect, we have made it to unload and get the specimen out for pictures during every loading stage. On the basis of comprehensive pictures and comparable strain–stress relationship, the specimen's failure phenomena and evolution laws are generalized.

3.1 Case 1 – stagger separation between both pre-fractures is 5 mm

For this test case, canchroids of both pre-fractures are not in a vertical line and they show a minimum distance among all cases. Front and lateral views of the specimen at some moments during its secondary fracture propagation are presented in Figure 7. Figure 8 shows the full stress–strain relationship curve and has been worked out by a specimen's uninterrupted loading, i.e. no pictures are taken throughout the test.

Figure 6: The loading equipment: MTS rock mechanical test system.

Figure 7: Front and lateral views during the fracture evolution (case 1). (1) Filament; (2) wrapping wing crack; (3) granophytic crack; (4) quasi-wrapping fracture surface; 5. petaloid crack. (a) Wing crack initiation in early stage 2. (b) Fracture state at the end of stage 2. (c) Fracture coalescence and splitting failure.

Figure 8: The specimen's full stress-strain relationship curve (case 1).

It can be seen from Figure 8 that the failure process of the specimen could be adequately divided into four stages: original pre-fracture compaction, quasi-elastic deforming and wing crack initiation, stable secondary fracture propagation and coalescence, and eventual accelerating fracture propagation that results in overall instability of the specimen. The four stages are exactly consistent with the traditional rock mechanical test. The entire process is analysed in detail as follows:

- (1) Section OA in Figure 8 is the original pre-fracture compaction stage, of which the stress rises from 0 to approximately 10.9% of peak strength.
- (2) Section AB represents quasi-elastic deforming and wing crack initiation stage, with stress increasing from 10.9% of peak strength to 77.9%. In this stage, the axial strain shows a linear growth with stress. When stress arrives at 44.3% of peak strength, wing crack emerges first at the lower end of pre-fracture 2. Then, it also arises at the upper end of pre-fracture 2 and soon in sequence at the lower end of pre-fracture 1. Secondary fractures propagate synchronously at the three ends with a roughly same scale. However, no wing crack or other secondary fracture is observed at the upper end of pre-fracture 2 for a long while, just as shown in Figure 7(a). At this early stage, a wrapping wing crack and a granophytic crack (similar size and shape to a piebaldness) are distributed at each of the three ends and grow continuously. With further loading, wing crack appears abruptly at the upper end of pre-fracture 2. Just at the same moment, secondary fractures at other three ends stop growing and it remains a long time until two quasi-wrapping fracture surfaces are

Figure 9: Uniaxial experimental results by Dyskin [16].

developed at the upper end of pre-fracture 2. The two quasi-wrapping fracture surfaces are equal in size and disconnected at the long axis' one endpoint. With continuous loading, all wrapping cracks expand further away from two pre-fractures steadily. This is in good consistency with results of [16] on one internal pre-fracture (Figure 9), i.e. a wrapping wing crack will be formed at both ends of internal pre-fracture's long axis. At the stage end, as shown in Figure 7(b), a wrapping wing crack located at the upper end of pre-fracture 1 has expanded to be a giant fracture surface like a petal, which is the so-called petaloid crack. In addition, no anti-wing crack is observed.

- (3) Section BC is stable secondary fracture propagation and coalescence stage, during which stress increases from 77.9% of peak strength to 90.9%. In this section, the stress-strain relationship curve grows slowly while the lateral deformation speeds up much more evidently. In this stage, the primary granophytic cracks at lower ends of both pre-fractures 1 and 2 were gradually absorbed by growing wrapping wing crack and then developed into petaloid cracks. The two quasi-wrapping fracture surfaces at the upper end of pre-fracture 2 have also integrated as an intact petaloid crack. The petaloid cracks are pretty large and distributed symmetrically at both pre-fractures. With further loading, the petaloid cracks between two pre-fractures begin to coalesce. All petaloid cracks propagate increasingly away from pre-fracture surfaces in the way of a curved surface.
- (4) Section CD is eventual accelerating fracture propagation and specimen failure stage, with stress starting from 90.9% of peak strength until specimen splitting failure. During this stage, all petaloid cracks continue propagating vertically and those at the upper end of pre-fracture 1 and the lower end of pre-fracture 2 have gradually evolved into giant vertical fractures. As mentioned before, if the petaloid cracks between pre-

fractures could grow vertically forever, then they will hardly connect as the two pre-fractures are not coincident in the vertical direction. However, for petaloid crack at the upper end of pre-fracture 2, an unexpected bending plane is observed at its front edge, which coalesces with the upper end of pre-fracture 1 (Figure 7(c)). Bearing capacity of the specimen starts to decline sharply. Intense cracking sounds can be identified. Ultimately, giant vertical fractures reach the specimen's surface and the specimen is macroscopically split.

In traditional tests on real rocks, the inner fracture evolution could hardly be observed. Moreover, the new resin material's transparency and brittleness have been enhanced greatly. It can better represent real rocks in brittle characteristics and the image results are lots clearer than before. Specifically, [16] (Figure 9) mainly focused on one internal pre-fracture and only presents fracture state of the specimen during stage 2 in this study. The material of [18] (Figure 10) possesses poor transparency for observation on internal fracture evolution. Yet in this study, the full test process is demonstrated along with displaying clear images of secondary fractures. The four stages are in good consistency with the traditional uniaxial rock compression test, which could suggest well the resin material's similarity to real rocks.

3.2 Cases 2 to 4 – stagger separation between both pre-fractures is 12, 20 and 30 mm, respectively

The three test cases have all gone through the aforementioned four stages. They generally share the same macro failure process with test case 1 yet with some distinctions.

Figure 10: Yanshuang's experimental results [18].

In case 2, the two pre-fractures coincide perfectly in the vertical direction. Front and lateral views during the fracture evolution are shown in Figure 11. When stress arrives at 45.5% of peak strength, wing crack emerges first at the lower end of pre-fracture 2. Subsequently, it also arises at the lower end of pre-fracture 1, the upper end of pre-fracture 2, and the upper end of pre-fracture 1 in sequence. Secondary fractures propagate synchronously at all four ends with the same scale, which differs greatly from case 1, just as Figure 11(a) by the end of stage 2. However, there are also differences in the fracture state regarding the four ends. First, there is merely a wrapping wing crack at the lower end of pre-

(a)

(b)

Figure 11: Front and lateral views during the fracture evolution (case 2). (1) Filament; (2) wrapping wing crack; (3) granophyric crack; (4) quasi-wrapping fracture surface; (5) petaloid crack; (6) giant quasi-wrapping fracture. (a) Fracture state at the end of stage 2. (b) Fracture state in stage 3.

fracture 1. Second, there is together a granophyric crack which is beside the wrapping wing crack at both the upper end of pre-fracture 1 and the lower end of pre-fracture 2. Third, the wrapping wing crack at the upper end of pre-fracture 2 is discontinuous and could be divided visually into three quasi-wrapping fracture surfaces. Finally, during stage 3 (Figure 11(b)), in which symmetrical petaloid cracks are formed at both pre-fractures, there is meanwhile a granophyric crack located on the top surface of pre-fracture 1. Besides, a giant discontinuous quasi-wrapping fracture surface has been developed at the lower end of pre-crack 2.

In case 3, the two pre-fractures are increasingly far away from each other, yet still overlap about halfway in the vertical direction. Front and lateral views during the fracture evolution are shown in Figure 12. When stress arrives at 44.6% of peak strength, wing crack emerges first at the lower end of pre-fracture 2, then in sequence arises at the lower end of pre-fracture 1, the upper end of pre-fracture 2, and at the last upper end of pre-fracture 1. Secondary fractures propagate synchronously at all four ends, which is the same with case 2, just as Figure 12 at the late stage 3. Small wrapping wing cracks and granophyric cracks have totally integrated and evolved into smooth petaloid cracks. There are also some tiny distinctions at this moment: To begin with, there is a granophyric crack on the bottom surface of pre-fracture 1. Moreover, the petaloid crack at the upper end of pre-fracture 2 is larger than that at the lower end of pre-fracture 1 by the time of coalescence.

Figure 12: Front and lateral views during the fracture evolution (case 3). (1) Filament; (2) petaloid crack; (3) granophyric crack; (4) quasi-wrapping fracture surface.

Figure 13: Front and lateral views during the fracture evolution at the middle of stage 2 (case 4). (1) Filament; (2) wrapping wing crack; (3) granophytic crack; (4) quasi-wrapping fracture surface.

In case 4, the two pre-fractures are far away enough and they exactly fail to overlap vertically. Front and lateral views during the fracture evolution are shown in Figure 13. When stress arrives at 46.74% of peak strength, wing crack emerges first at the lower end of pre-fracture 2. Subsequently, wing crack then in sequence arises at the lower end of pre-fracture 1, the upper end of pre-fracture 2, and at last the upper end of pre-fracture 1. Secondary fractures propagate synchronously at all four ends with a roughly same scale, which is the same with cases 2 and 3 and thus differs greatly from case 1, just as Figure 13 at the middle of stage 2. It can be seen that with increase in stagger separation, the two pre-fractures interact much less and therefore make this case a maximum strength of all, about 92 MPa.

4 Analysis and comparison on experimental results

In this section, failure laws of the four cases are generalized and the impact of stagger separation is illustrated.

4.1 Failure phenomena in common

- (1) There are macroscopic phenomena in common. First, all specimens have gone through four stages

as traditional rock test regarding fracture initiation, propagation, and coalescence. Moreover, diverse forms of secondary fractures, such as wrapping wing crack, granophytic crack, and petaloid crack, have appeared. Finally, all specimens are ultimately split by giant vertical fractures that evolve from petaloid cracks.

- (2) In all experiments, secondary fractures are simply wing cracks, i.e. no anti-wing crack is identified. The fracture initiation and propagation are closely associated with inflection points of the volumetric strain. Positions of fracture initiation are all at or extremely close to the endpoints of pre-fractures.
- (3) The granophytic cracks are roughly as big as a mung bean. They arise beside secondary fractures' outer edges but do not then propagate exactly along the edge of pre-fractures. Particularly, there is an included angle between them and the edge of pre-fractures. Subsequently, they are steadily absorbed by the growing wrapping wing crack or petaloid crack, promoting new-formed secondary fractures to propagate toward the specimen's lateral surface.
- (4) Fracture evolution of the new material shows good consistency with those of [16,18]. Yet [16] (Figure 9) mainly focused on one internal pre-fracture and only presents fracture state of the specimen during stage 2 in this study. The material of [18] (Figure 10) possesses poor transparency for observation on internal fracture evolution. In this study, the full test process is demonstrated along with displaying clear images of secondary fractures.

4.2 Fracture initiation stress and specimen peak strength

Within loading, there are distinct cracking sounds from interior of the specimen when secondary fracture initiates as a result of high brittleness, somewhat like breaking off a brittle plastic sheet. Besides, micro changes can be visually observed as the post-failure zones are quite different from their surroundings. In general, it is based on the above detectable phenomena that the fracture initiation stress of each case is figured out.

For all cases, their secondary fractures initiate first at the lower end of pre-fracture 2, with axial stress around 45% of peak strength. Table 3 displays the corresponding stresses. Actually, fracture initiation

Table 3: Corresponding stresses of the four cases

No.	Stagger separation b /mm	σ_c /MPa	σ_i /MPa	σ_i/σ_c (%)	σ_i/σ_c at either end of both pre-fractures			
					Upper end of pre-fracture 1 (%)	Lower end of pre-fracture 1 (%)	Upper end of pre-fracture 2 (%)	Lower end of pre-fracture 2 (%)
1	5	81	35.88	44.30	49.30	54.30	70.40	44.30
2	12	83	37.77	45.50	55.6	49.3	51.5	45.50
3	20	87	38.8	44.60	62.10	56.20	60.20	44.60
4	30	92	43	46.74	62.30	53.30	58	46.74

σ_i – wing crack initiation stress; σ_c – specimen peak strength.

stresses are all within a specific range with limited difference, just as Figure 14. Then, secondary fracture at the lower end of pre-fracture 1 initiates in sequence (except case 1 which is at the upper end of pre-fracture 1). Subsequently, secondary fracture also initiates orderly at the upper end of pre-fracture 1 or that of pre-fracture 2; no fixed sequence is identified. It is worth mentioning that fracture initiation at the upper end of pre-fracture 2 is significantly slow in case 1, lots slower than that at other three pre-fracture ends.

As to peak strength, it can be seen from Figure 14 that it is not so sensitive to stagger separation as the total number of pre-fractures is fixed to be two. The maximum difference between peak strengths of all cases, i.e. cases 1 and 4, is merely 11 MPa, accounting for just 10% of peak strength. Besides, with the increase of stagger separation, both pre-fractures show less interaction with each other and the peak strength therefore makes an accelerated growth.

Figure 14: The impact of stagger separation on fracture initiation stress and peak strength. σ_i – wing crack initiation stress; σ_c – specimen peak strength.

4.3 Distinct failure laws

There are individual differences that can also be indicated from Table 3. First, for case 2, of which the stagger separation is 12 mm and pre-fractures are vertically coincident, its fracture initiations at four pre-fracture ends are almost at the same time. Its secondary fractures at four ends develop synchronously and are dynamically in the same scale. Second, in other three cases, where the projections of two pre-fractures overlap just a small part in the vertical direction, fracture initiations at four ends differ greatly. Furthermore, secondary fractures at four ends develop with different scales and seldom synchronously. Third, positions of granophytic cracks are quite different among all cases. Finally, the coalescences of pre-fractures are also different, like the distinct bending plane in case 1 for pre-fracture coalescence.

Thus, it can be seen that for all cases, despite some differences in the initiation of wrapping wing cracks and positions of granophytic cracks, other things such as fracture initiation and secondary fracture propagation laws, especially the wrapping wing cracks, petaloid cracks and specimen failure, are generally in good consistency and mainly depend on the shape of pre-fractures and experiment loading mode.

5 Conclusions

- (1) A self-developed resin material has been introduced. It is highly transparent and the ratio of tension–compression strength can be 1/6.6 at -10 to -15°C . Compared with 1/3 obtained by former scholars, the new resin material's brittleness has been enhanced greatly and can better represent real rocks in brittle characteristics. Its transparency is as well improved and image results are lots clearer than before.

- (2) A set of preparation, casting mould, and post-processing technologies were established and specimens with double parallel internal fracture surfaces yet of four different stagger separations are made. Uniaxial tests were carried out and the stress–strain relationship is analysed. It is shown that the specimen has gone through four stages the same as the traditional rock test before failure. The new resin also shows obvious dilatancy characteristics like real rocks.
- (3) For all cases, the stagger separation makes a stable influence on the specimen failure process. With its increase, the two pre-fractures interact less and therefore both the fracture initiation stress and peak strength make a slight growth at an accelerated speed. The failure evolutions are also different in many aspects, such as the distinct bending plane in case 1 for pre-fracture coalescence and the asynchronous evolution of wrapping wing cracks.
- (4) Some failure phenomena are revealed which have not been reported before, such as the evolution of quasi-wrapping fractures and coalescence manners of pre-fractures. Besides, many diverse forms of secondary fractures, such as wrapping wing crack, petaloid crack, and giant quasi-wrapping fracture surface, which were not found in 2D conditions have appeared and their evolutions were clearly seen in each stage.

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