Research Article

Effects of Flaw Geometry on the Fracturing Behavior of Rock-Like Materials Containing Two Arch-Like Parallelogram Flaws

Longqing Shi\textsuperscript{1,2} and Dongjing Xu\textsuperscript{1,2}

\textsuperscript{1}Shandong Provincial Key Laboratory of Depositional Mineralization & Sedimentary Minerals, Shandong University of Science and Technology, Qingdao 266590, China
\textsuperscript{2}College of Earth Sciences & Engineering, Shandong University of Science and Technology, Qingdao 266590, China

Correspondence should be addressed to Dongjing Xu; xudongjinggg@126.com

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To increase understanding of the strength and failure mechanism of rocks with arch-like fractures generated in the overlying strata above a gob during coal mining, a series of uniaxial compression tests on rock-like specimens containing two preexisting parallelogram flaws at inclination angles varying from 45° to 75° were made using a rock mechanics servocontrolled testing system. Based on the experimental results, the effects of the inclination angles of two flaws having the same area on the mechanical parameters and fracturing process of the specimens were analyzed in detail. By adopting photographic monitoring, the crack initiation, propagation, coalescence, and failure modes in rock-like specimens were observed and characterized. The crack initiation stress and the second initiation stress were distinctly related to the flaw inclination angles, although the crack initiation stress presented a change trend generally similar to that of the crack second initiation stress with increasing flaw angle. Four modes of ultimate macroscopic failure morphology and the crack coalescence and failure modes of three types could be summarized. The research reported here could provide some theoretical support for the arch-like fracture evolution in the overburden during the excavation in underground engineering, especially in coal mining engineering.

1. Introduction

Critical engineering projects such as underground mining and undersea tunnels are prone to damage from the existence of discontinuities consisting of faults, weak surfaces, joints, cracks, and fissures, which significantly affect the mechanical characteristics of the rocks such as deformation, strength, and fracture behavior [1–6]. Such discontinuities decrease the strength and stiffness of the rocks, and, under the effects of external mechanical forces, discontinuities cause new cracks that in turn propagate along with other growing cracks and then coalesce, thereby leading to failure of the rock mass [7, 8].

The cracking behavior of natural rocks and rock-like specimens containing preexisting flaws under uniaxial compression has been experimentally and numerically studied for the past few decades [9–11]. In terms of rock specimens, different specimen sizes ranging from a small size of 50 mm × 32 mm × 5 mm to a large size of 635 mm × 279 mm × 203 mm have been used for studying the mechanical modes of rocks [12, 13]. The specimen shapes and materials tested by different research organizations have also varied [14]. The former takes two main forms including cubes and cylinders, and the latter consists of sandstone [15], marble [16], limestone [17], granite, granodiorite [18], and clay [19], among natural rocks, and glass and Columbia Resin 39, plaster of Paris, polymethyl methacrylate (PMMA) [20], molded gypsum, cement mortar [21], composite material, and so forth, among similar materials. In addition, in terms of preexisting flaws, great efforts have been made to simulate different flaw geometries and numbers [22], which can be easily fabricated by inserting paper, mica, or steel discs. The geometries include changing the values of the flaw inclination angle, the bridge ligament angle and the spacing...
2.1. Sample Geometry and Preparation. According to the theory of the trapezoidal broken model established by Xu et al. [11, 30, 31], the fracture patterns in massive strata controlled by the volume expansion coefficient were obtained, and the consequent fracture parameters were calculated to investigate the fracture formation mechanism in the overburden strata due to caving caused by coal mining. In this model, a series of parallelogram fractures were produced at both ends of the trapezoidal broken model (Figure 1), and each parallelogram was defined by its long side \((a)\), short side \((b)\), height \((h)\), area \((S)\), and dip inclination \((\alpha)\) [11].

As shown in Figure 2, the dimensions of the sample in the present study are 100 mm × 50 mm × 50 mm (length × width × thickness). The geometric parameters of the arch-like prefabricated flaws include the left flaw inclination angle \((\alpha)\), angle between the left flaw long side and the horizontal axis), right flaw inclination angle \((\beta)\), angle between the right flaw long side and the horizontal axis), flaw height \((h)\), long side \((a)\), short side \((b)\), and ligament \((l)\). Additionally, the two interpenetrated flaws are created by a thin steel sheet. The short side and the height of each flaw are the same and are fixed at 2 mm and 5 mm, respectively. The distance between the upper inner tips of the two prefabricated flaws is fixed at 5 mm, and the inclination angles of the flaws \((\alpha\) and \(\beta)\) initially vary from 45° to 60° to 75° (15° intervals) with the value of \(a\) less than or equal to that of \(\beta\). A detailed description of these tested samples with different flaw geometries is presented in Table 1 [11].

The specimen mold is made of about 8–15 mm thick steel plate. It is assembled from 4 detachable steel plates connected by milling grooves. On the base steel plate, there are two 5 mm deep grooves for setting cracked steel plates of different inclination angles. The cracked steel plates can be inserted in the groove by using laser cutting technology to ensure the flatness of the steel plate. The cracked part is first scribed at the bottom of the center of the steel plate, and the crack is placed in the bottom groove. The cracked part is a cracked slice made of stainless-steel plate with the thickness of 2 mm. The internal dimensions of the mold are formed with the length, width, and height of 100 mm × 50 mm × 50 mm.

In this experiment, fine sand (size distribution, 0.15–0.30 mm) was used as the skeletal material, along with the cement as the cementing material, to combine the fine sand. The ratio of the material compositions including cement, fine sand, and water is 26 : 25 : 10 (weight). In this way, not only is the brittle behavior of the rock satisfied, but also it is more likely to observe the fracturing processes and strength variations in rock-like materials having more uniform distribution of particles unlike natural rocks. Based on similar mechanical properties with natural rocks, cement mortar samples were put to this study [11].

2.2. Testing Procedure. All uniaxial compression tests on prepared specimens with the same flaw areas were conducted with a rock mechanics servocontrolled testing system having an axial displacement rate of 0.1 mm/min (seen in Figure 3) to obtain the mechanical properties. A specimen was loaded until it failed or until cracks had coalesced under uniaxial compression conditions. Each loading process was recorded by a high-speed camera (FASTCAM SA1.1) to detect new crack initiation, propagation, and coalescence, which were observed with the support of the Photron FASTCAM Viewer. FASTCAM SA1 uses the latest CMOS sensor to achieve sensitivity and speeds previously unattainable. It is capable
of 5,400 full frames per second (fps) at mega pixel (1 K×1 K) resolution. Additionally, by testing intact specimens with no flaw, the mechanical parameters and stress-strain curves of the intact specimens were obtained for comparison with those of the specimens with flaws [11].

3. Results and Discussion

3.1. Stress Analysis in Specimens. The axial stress-strain curves of the specimens under uniaxial compression tests are shown in Figure 4. Considering the differences in specimens with the same flaw geometry caused by material distribution
and so on, the tests of three specimens for each flaw geometry should have been repeated to obtain the best possible results. Generally, the effects of specimen variability for the same flaw areas on the mechanical parameters are small. However, note that the axial stress-strain curves for specimens with the same flaw inclination angle vary due to different crack coalescence processes in the rock specimens, which can be seen in Figure 4 [11].

From Figure 4, we can also see that specimens with or without flaws show initial nonlinear deformation, mainly resulting from the closure of internal particles in the material. Then, the axial stress presents a nearly linear relation with the axial strain, indicating the beginning of elastic deformation. After that, there exists a longer stage of plastic deformation in the preexisting flawed specimens for $\alpha$ and $\beta$ less than 45° and 60° (seen in Figures 4(a)–4(c)). Figure 5 shows the axial stress-strain curves of the specimens with two flaws and inclination angles ranging from 45° to 75°.

Figure 5 shows the axial stress-strain curves of specimens with two flaw inclination angles ranging from 45° to 75°, which are selected from the axial stress-strain curves with similar trends in Figures 4(a)–4(f). From Figure 5, we can observe that specimens with different flaw inclination angles have dissimilar development tendencies in the stress-strain curves. However, the curves of specimens with relatively lower flaw inclination angles such as $\alpha = \beta = 45^\circ$ and $\alpha = 45^\circ < \beta = 75^\circ$ are more concentrated, and these curves are quite different from those of specimens with higher flaw inclination angles, which are also shown to be concentrated. Additionally, all curves for flawed specimens are obviously different from those of intact specimens.

**3.2. Strength and Deformation Behavior in Specimens Containing Two Parallelogram Flaws.** The effects of the orientation of flaws with the same area on the strength and deformation parameters of specimens containing two parallelogram flaws are shown in Figure 6. The peak strength, peak strain, and elastic modulus of intact specimens are obtained from the experiment, namely, 59.39 MPa, $13.85 \times 10^{-3}$, and 5.73 GPa, respectively. As shown in Figure 6(a), the peak strength and peak strain of prefawed specimens are significantly lower than those of intact specimens, and the elastic modulus is slightly less than that of intact specimens, demonstrating a greater influence of the preexisting flaws on the peak strength and peak strain than on the elastic modulus of specimens [11].

| Type | Number | $L$ (mm) | $W$ (mm) | $T$ (mm) | $\alpha$ (°) | $\beta$ (°) | $b$ (mm) | $h$ (mm) |
|------|--------|----------|----------|----------|-------------|-------------|---------|---------|
| TA5  | 1      | 100.1    | 49.8     | 50.0     | 45          | 45          | 2       | 5       |
| TA5  | 2      | 100.0    | 50.2     | 50.1     | 45          | 45          | 2       | 5       |
| TA5  | 3      | 100.1    | 50.1     | 49.7     | 45          | 45          | 2       | 5       |
| TA5  | 4      | 100.2    | 50.0     | 49.8     | 45          | 60          | 2       | 5       |
| TA5  | 5      | 100.2    | 50.0     | 50.1     | 45          | 60          | 2       | 5       |
| TA5  | 6      | 99.9     | 50.1     | 50.0     | 45          | 60          | 2       | 5       |
| TA5  | 7      | 100.1    | 50.1     | 50.0     | 45          | 75          | 2       | 5       |
| TA5  | 8      | 100.2    | 49.7     | 50.2     | 45          | 75          | 2       | 5       |
| TA5  | 9      | 100.3    | 49.8     | 49.9     | 45          | 75          | 2       | 5       |
| TA5  | 10     | 100.0    | 49.9     | 49.7     | 60          | 60          | 2       | 5       |
| TA5  | 11     | 100.0    | 50.1     | 49.8     | 60          | 60          | 2       | 5       |
| TA5  | 12     | 99.8     | 50.0     | 50.0     | 60          | 60          | 2       | 5       |
| TA5  | 13     | 99.9     | 50.2     | 50.2     | 60          | 75          | 2       | 5       |
| TA5  | 14     | 100.1    | 49.9     | 50.3     | 60          | 75          | 2       | 5       |
| TA5  | 15     | 100.2    | 49.8     | 50.1     | 60          | 75          | 2       | 5       |
| TA5  | 16     | 100.1    | 50.3     | 49.8     | 75          | 75          | 2       | 5       |
| TA5  | 17     | 100.2    | 50.2     | 49.8     | 75          | 75          | 2       | 5       |
| TA5  | 18     | 100.3    | 50.2     | 50.0     | 75          | 75          | 2       | 5       |
| No flaw |      |         |          |          |             |             |         |         |
| $I$-1 |      | 100.1    | 49.8     | 50.2     | —           | —           | —       | —       |
| $I$-2 |      | 99.9     | 49.8     | 50.3     | —           | —           | —       | —       |
| $I$-3 |      | 100.1    | 49.7     | 50.2     | —           | —           | —       | —       |

*Table 1: Tested sample geometries containing two prefabricated flaws under uniaxial compression.*

*Note. TA5: the specimens having the prefabricated flaws (the subscript means ligament), $I$: intact rock, $L$: length of sample, $W$: width of sample, and $T$: thickness of sample.*

Figure 3: Testing process and main equipment used [11].
The relationship between the peak strength and the two flaw inclination angles is displayed in Figure 6(a). As shown in Figure 6(a), the peak strength generally presents an approximately linear trend with increasing flaw inclination angle. As the flaw inclination angle increases, the peak strength first increases rapidly and then gradually declines and finally increases sharply and nearly in accordance with the overall trend. When the two flaw inclination angles increase from \( \alpha = \beta = 45^\circ \) to \( \alpha = 45 < \beta = 60^\circ \) with a 15\(^\circ\) angle increase in either of the two flaws, the peak value increases from 39.76 MPa to 43.43 MPa. When the angle increases from \( \alpha = 45 < \beta = 60^\circ \) to \( \alpha = 45 < \beta = 75^\circ \) with a 15\(^\circ\) angle increase in...
Figure 5: Stress-strain curves of specimens containing no parallelogram flaws (left) and two preexisting parallelogram flaws at different angles (right) under uniaxial compression.

Figure 6: Continued.
The relationship between the peak strain and the two flaw inclination angles is plotted in Figure 6(b). As shown in Figure 6(b), aside from the value of $a = 45 < \beta = 60^\circ$, the peak strain also presents a generally nonlinear and progressive increase with increasing flaw inclination angle, which is similar to that of the peak strength as a whole. When the flaw inclination angle increases from $a = \beta = 45^\circ$ to $a = 45 < \beta = 60^\circ$ with a $15^\circ$ angle increase in either of the two flaws, the peak strain sharply increases from $9.58 \times 10^{-3}$ to $10.97 \times 10^{-3}$. Then, as the flaw inclination angle increases from $a = 45 < \beta = 60^\circ$ to $a = 45 < \beta = 75^\circ$, the peak strain considerably declines from $10.97 \times 10^{-3}$ to $10.32 \times 10^{-3}$. Finally, as the flaw inclination angle increases from $a = 45 < \beta = 75^\circ$ to $a = \beta = 75^\circ$, the peak strain gradually increases from $10.32 \times 10^{-3}$ to $12.62 \times 10^{-3}$ in a trend from slow to fast.

The relationship between the elastic modulus and the two flaw inclination angles is presented in Figure 6(c). As shown in Figure 6(c), the elastic modulus obviously increases at first and then generally decreases while varying within a small range. When the flaw inclination angle increases from $a = \beta = 45^\circ$ to $a = 45 < \beta = 75^\circ$, the elastic modulus gradually increases from 5.48 GPa to 5.69 GPa. However, along with an increase in the flaw inclination angle from $a = 45 < \beta = 75^\circ$ to $a = \beta = 75^\circ$, the elastic modulus decreases from 5.69 GPa to 5.45 GPa, except for a fluctuation in the elastic modulus (5.56 GPa) for angle values of $a = \beta = 75^\circ$.

Additionally, through the above analysis, we can see that Figure 6(a) somewhat resembles Figure 6(b) for flaw inclination angles of $a = 45 < \beta = 75^\circ$ and $a = \beta = 60^\circ$. That is, the former angles produce relatively lower values than the latter in the peak strength and peak strain, although the sum of the two flaw inclination angles in both specimens is equal, which reveals the influence of the difference in the variation.
between the two flaw inclination angles with the same area on the peak strength and peak strain. This analysis indicates that greater differences between the two flaw inclination angles can reduce the peak strength and peak strain more sharply.

3.3. Crack Initiation, Propagation, and Failure Behavior

3.3.1. Crack Initiation and Propagation Stress. The crack initiation and second initiation stresses are defined as the stresses when the first and second new crack initiations are found individually with the naked eye, whereas the peak stress is obtained by the rock mechanics servocontrolled testing system. As seen in Figure 7, the crack initiation stress presents a change trend generally similar to that of the crack second initiation stress with increasing flaw inclination angles. Furthermore, the magnitude of the latter is slightly higher than that of the former for flaw inclination angles of α = β = 45° to α = β = 60° (the difference range is from 0.73 MPa to 2.46 MPa), but the latter is noticeably higher than the former for flaw inclination angles of α = 60° < β = 75° (the difference is 4.87 MPa); no data are visible for the crack second initiation stress with flaw inclination angles of α = β = 75°. By comparing the differences between the magnitudes of crack initiation stress and peak stress, we can see that there is a relatively greater difference at both ends of the flaw inclination angles including α = β = 45°, α = 60° < β = 75°, and α = β = 75° and a minor difference in the middle section. The differences for the specimens at both ends are 12.62 MPa, 6.82 MPa, and 4 MPa, respectively, whereas that in the middle section is in the range from 2.06 MPa to 2.84 MPa, which may be caused by longer flaw length and more flaw concentration. Furthermore, when the flaw inclination angles are α = 60° < β = 75° and α = β = 75°, the flaw length is relatively shorter than others and causes crack initiation stress to begin rather late; also, it has a slight impact on rock strength and slowly reaches the peak stress. However, the flaw inclination angles for α = β = 45° show larger difference between the magnitude of the crack initiation stress and the peak stress than that of α = 60° < β = 75° and α = β = 75°, which might present that flaw length has more influence on the specimens than flaw concentration for each flaw with the same area.

3.3.2. Crack Initiation Behavior. As is well known, new cracks are always observed to initiate at the tips of nearby preexisting flaws under an applied load, and these new cracks expand approximately in the direction parallel to the maximum principal stress in the flawed specimens, leading to coalescence of the cracks before unstable failure. Table 2 shows the macro first cracks initiated from specimens containing two parallelogram flaws at different angles under uniaxial compression in a period of time. As seen in Table 3, more secondary cracks are observed at the tips of the flaw with the smaller inclination angle. Furthermore, more wing cracks appear in cases with flaw inclination angles of α = 45° < β = 60° and α = 60° < β = 75° upon further loading. Meanwhile, more minor cracks along the direction parallel to the maximum principal stress are discovered in the neighborhood below the lower tips of the two flaws, which are the positions where stress concentration or confinement increases. In this experiment, the secondary cracks are relatively numerous and complicated and are mainly concentrated in the neighborhoods below and above the two flaws when the prefabricated flaw inclination angle is small (α = β = 45°, α = 45° < β = 60°, α = 45° < β = 75°, and α = β = 60°).

3.3.3. Crack Propagation Behavior. Table 3 shows the macro crack propagation process for specimens containing two parallelogram flaws at different angles under uniaxial compression in a period of time. As seen in Table 3, more secondary cracks are observed at the tips of the flaw with the smaller inclination angle. Furthermore, more wing cracks appear in cases with flaw inclination angles of α = 45° < β = 60° and α = 60° < β = 75° upon further loading. Meanwhile, more minor cracks along the direction parallel to the maximum principal stress are discovered in the neighborhood below the lower tips of the two flaws, which are the positions where stress concentration or confinement increases. In this experiment, the secondary cracks are relatively numerous and complicated and are mainly concentrated in the neighborhoods below and above the two flaws when the prefabricated flaw inclination angle is small (α = β = 45°, α = 45° < β = 60°, α = 45° < β = 75°, and α = β = 60°).
When the flaw inclination angles are larger than $\alpha = 60 < \beta = 75^\circ$, the lower-wing crack at the lower outer tip of the left flaw develops in the direction parallel to the maximum principal stress at first and then expands along the direction of the flaw inclination angle. However, the upper-wing crack at the upper inner tip of the left flaw always develops nearly in the direction parallel to the maximum principal stress. One of the two flaws with inclination angles of $\alpha = 75^\circ$ has the same behavior. These cracks illustrate the important influence of flaw inclination angles in the specimen on its crack propagation behavior, showing a large difference between the smaller and larger angles of the preexisting flaws in the specimens; one flaw at a smaller angle more easily first produces intact wing cracks or cracks at the tips of the flaws.

### 3.3.4. Crack Coalescence and Failure Behavior

Table 4 shows the sketch of macro crack coalescence process for specimens containing two parallelogram flaws with different angles under uniaxial compression. As seen in Table 4, the crack coalescence patterns are very different with respect to flaw inclination angles, $\alpha$ and $\beta$. In the specimens for $\alpha = \beta = 45^\circ$, the tensile wing cracks emanating from two flaw tips or near the tips continue to develop along the direction parallel to the maximum principal stress, with relatively more secondary cracks generated from a lower-angle flaw propagating in the same way. However, the specimens for $\alpha = 45 < \beta = 75^\circ$, the new cracks continue to propagate along the direction of the initial cracks and then extend to the boundary of the specimen. Although more cracks occur in the middle part between the two flaws, no obvious coalescence process happens in this position. Under the effect of the antiwing cracks at the tips of a lower-angle flaw and the shear cracks at the lower outer tip of the same flaw, a process of crack coalescence occurs near the right part of this flaw. It also seems to suggest that the trend of crack coalescence at or around the middle part above the upper tips of the flaws becomes more and more apparent. In the specimens for $\alpha = \beta = 45^\circ$, $\alpha = 60 < \beta = 75^\circ$, and $\alpha = \beta = 75^\circ$, the shear cracks along the direction of the two flaws obviously grow and then propagate and coalesce at or around the middle part above the upper tips of the flaws to form an obvious inverse V. Meanwhile, there are a few secondary cracks in the specimens of this angle range, showing a relatively more focused stress concentration. To sum up, we can easily see that there is a growing trend of crack coalescence in the middle part above the upper tips of the flaws as the arch-like flaw angle increases, which may present a growth of stress concentration in this position.

Table 5 shows the ultimate failure modes of the specimens containing two parallelogram flaws at different angles under uniaxial compression. As seen in Table 5, the main types of cracks can be categorized as wing cracks, antiwing cracks, shear cracks, secondary cracks, and surface spalling and far-field cracks (seen in Table 5), which often occur in the crack images on the basis of analyzing the failure modes of specimens. In addition, the cracks in failed specimens from the experiment are a mixture of various crack types, the characteristics of which are not discussed in detail here. The fact that the failure of flawed specimens is always caused by the expansion and coalescence of cracks after the occurrence of crack initiation from preexisting flaws is well known.
The crack coalescence and failure modes depend largely on the inclination angles of the two flaws in a single specimen, which are shown in Table 5. These modes can be summarized into three distinct types as described below.

(i) Type I: the two main cracks starting at the upper tips of both flaws develop their own trajectories in almost the direction parallel to the maximum principal stress and they do not link until failure of the specimen. In brief, no crack coalescence failure occurs at the tips of both flaws when $\alpha = \beta = 45^\circ$ and $\alpha = 45^\circ < \beta = 60^\circ$.

(ii) Type II: the two main cracks starting at the lower outer tip of the flaw with the smaller inclination angle propagate outward (one toward the upper middle part of the side edge and the other toward the lower middle part of the side edge), possibly because of the large flaw angle difference ($30^\circ$) in the flawed specimen, which also indicates strong lateral damage and is very different from other failure modes. In brief, cracks directly fail by outward divergence from the lower outer tip of one flaw along with a powerful transverse influence when $\alpha = 45^\circ < \beta = 75^\circ$.

(iii) Type III: the two main cracks starting at the upper inner tips of both flaws develop along the respective flaw directions, followed by crack coalescence and a broadening failure in the direction parallel to the maximum principal stress. In brief, obvious crack coalescence failure occurs at some distance above the tips of both flaws when $\alpha = \beta = 60^\circ$, $\alpha = 60^\circ < \beta = 75^\circ$, and $\alpha = \beta = 75^\circ$. 

Table 3: Macro crack coalescence process in the specimens containing two parallelogram flaws with different angles under uniaxial compression.

| $\alpha - \beta$ (degree) | 45–45 | 45–60 | 45–75 | 60–60 | 60–75 | 75–75 |
|--------------------------|-------|-------|-------|-------|-------|-------|
| Crack coalescence process| ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) | ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png) |

Table 4: Sketch of macro crack coalescence process in the specimens containing two parallelogram flaws with different angles under uniaxial compression (the light-blue lines represent the initial cracks and the dark-blue lines represent the new cracks emanating from the initial cracks).

| $\alpha - \beta$ (degree) | 45–45 | 45–60 | 45–75 | 60–60 | 60–75 | 75–75 |
|--------------------------|-------|-------|-------|-------|-------|-------|
| Crack coalescence process| ![Image](image7.png) | ![Image](image8.png) | ![Image](image9.png) | ![Image](image10.png) | ![Image](image11.png) | ![Image](image12.png) |
In addition, the macro failure cracks starting from the flaw with the smaller inclination angle generally develop well and often become main failure paths. Moreover, the main cracks starting at the upper tips of both flaws develop a higher concentration upward and are relatively fewer than those at the lower tips of both flaws, showing an indication of higher stress compression or confinement increases for the former than for the latter, which is a significant difference in the effects between the geometries of arch-like prefabricated flaws and others on the crack coalescence and failure behavior.

From Table 5, we can also see that, according to the ultimate macroscopic failure morphology, four modes can be summarized: C-shaped mode ($\alpha = \beta = 45^\circ$ and $\alpha = \beta = 60^\circ$), herringbone mode ($\alpha = 45 < \beta = 60^\circ$), inverse C-shaped mode ($\alpha = 60 < \beta = 75^\circ$), and X-shaped mode ($\alpha = \beta = 75^\circ$).

3.3.5. Characteristics of Surface Cracks in Ultimate Failure Modes of the Specimens. ImageJ is an image processing and analysis software, which is written in Java, allowing the analysis on the measure of area, lengths, angles, and so on. It uses real-world measurement units such as millimeters. In this paper, we use this software to get the binary images of the surface cracks in ultimate failure modes of all specimens and then identify the surface cracks area (crack area $>2 \text{ mm}^2$) and their angles. The horizontal axis stands for the dip angles of the identified surface cracks, and the vertical axis shows the percentage of crack area at different dip angles accounting for all surface cracks areas. As seen in Tables 6–8, we can see that the displayed flaw angle means the actual identified flaw dip angle; for example, the dip angle of the prefabricated flaw, $\alpha = 60 < \beta = 75^\circ$, is presented in the table as $120^\circ$ and $75^\circ$, respectively. In these tables, the statistical dip angles are the angles between all identified cracks’ direction and the direction of $x$-axis.

As can be seen in Tables 6–8, crack binarization images and the distribution of main cracks dip angle in ultimate failure modes of the specimens containing two parallelogram flaws at different angles are presented. In the specimens for $\alpha = \beta = 45^\circ$ (displayed flaw angle, 135° and 45°), the cracks dip angle focuses on the range of 90°–100° and 65°–70°, and the percentage of the former is slightly larger than that of the latter, both of which are much larger than the range of 40°–50°, indicating that the direction of surface cracks mainly develops in the load direction, and the combined effect between flaw dip angle and load direction takes second place. In the specimens for $\alpha = 45 < \beta = 60^\circ$ (displayed flaw angle, 135° and 60°), the cracks dip angle focuses on the range of 50°–55° and 85°–100°, and the percentage of the former is slightly larger than that of the latter, both of which are much larger than the range of 120°–125°, indicating that the direction of surface cracks mainly develops in a higher-angle flaw direction of two arch-like prefabricated flaws, and the load direction second only to it, and yet the lower-angle flaw has a little influence on the dip angle of these cracks. In the specimens for $\alpha = 45 < \beta = 75^\circ$ (displayed flaw angle, 135° and 75°), the cracks dip angle focuses on the range of 50°–55° and 105°–120°, and the percentage of the former is twice as large as that of the latter, indicating that the combined effect between a lower-angle flaw direction and load direction accounts for a dominant position, having the direction along a higher-angle flaw in second place. In the specimens for $\alpha = \beta = 60^\circ$ (displayed flaw angle, 120° and 60°), the cracks dip
Table 6: Crack binarization images and the distribution of main cracks dip angle in ultimate failure modes of the specimens containing two parallelogram flaws at $\alpha=\beta=45^\circ$, $\alpha=45^\circ < \beta=60^\circ$, and $\alpha=45^\circ < \beta=75^\circ$ under uniaxial compression.

| $\alpha-\beta$ (degree) | 45–45 | 45–60 | 45–75 |
|-------------------------|-------|-------|-------|
| Crack binarization images | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) |
| Main cracks dip angle | ![Graph](graph1.png) | ![Graph](graph2.png) | ![Graph](graph3.png) |

Table 7: Crack binarization images and the distribution of main cracks dip angle in ultimate failure modes of the specimens containing two parallelogram flaws at $\alpha=\beta=60^\circ$, $\alpha=60^\circ < \beta=75^\circ$, and $\alpha=\beta=75^\circ$ under uniaxial compression.

| $\alpha-\beta$ (degree) | 60–60 | 60–75 | 75–75 |
|-------------------------|-------|-------|-------|
| Crack binarization images | ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png) |
| Main cracks dip angle | ![Graph](graph4.png) | ![Graph](graph5.png) | ![Graph](graph6.png) |

Angle focuses on the range of $65^\circ$–$70^\circ$ and $100^\circ$–$115^\circ$, and the percentage of the former is as much as that of the latter, both of which are much larger than the cracks dip angle range of $85^\circ$–$95^\circ$, indicating that the direction of surface cracks mainly develops in the direction of two arch-like prefabricated flaws, and yet the load direction has a little influence on the dip angle of these cracks. In the specimens for $\alpha=60^\circ < \beta=75^\circ$ (displayed flaw angle, $120^\circ$ and $75^\circ$), the cracks dip angle focuses on the ranges of $100^\circ$–$110^\circ$ and $70^\circ$–$80^\circ$, and the percentage of the former is slightly as large as that of the latter, both of which are much larger than the cracks dip angle range of $85^\circ$–$90^\circ$, indicating that the direction of surface cracks mainly develops in the load direction. In the specimens containing no parallelogram flaws, the cracks dip angle mostly focuses on the range of $65^\circ$–$80^\circ$.

As the above analysis shows, there is a big difference in the distribution of main cracks dip angle in ultimate failure modes of the specimens containing two parallelogram flaws at different angles from $\alpha=\beta=45^\circ$ to $\alpha=\beta=75^\circ$. In the specimens at both ends of flaw angles, the direction of main cracks dip angle may mostly be controlled by the load direction. However, in the specimens at the middle range of flaw angles, the direction of main cracks dip angle may mostly be controlled by the direction of two arch-like prefabricated flaws; thus the arch-like prefabricated flaws present a big impact on the dip angle development of surface cracks in ultimate failure modes of the specimens and cause new cracks to evolve along the direction of the flaw inclination angle.

From the experimental result, we can know that the crack fractal dimension value in ultimate failure modes of
the specimens containing no parallelogram flaws is 1.48. As can be seen from Figure 8, it can also be concluded that the fractal dimension of surface cracks presents a generally increasing trend, except the specimens for $\alpha = \beta = 45^\circ$ with the lowest value (the fractal dimension value, 1.20), indicating that the specimens under uniaxial compression have a shorter time to break, a more concentrated failure, and more developed fracture growth as flaw angle increases. In the specimens for $\alpha = \beta = 75^\circ$, the crack fractal dimension value is extremely high, whereas the specimens for $\alpha = 45 < \beta = 60^\circ$, $\alpha = 45 < \beta = 75^\circ$, and $\alpha = 60 < \beta = 75^\circ$ have a similar and stable fractal dimension value in the range of 1.30–1.32, whose value is slightly higher than that of the specimens for $\alpha = \beta = 45^\circ$ (the fractal dimension value, 1.25), indicating that two different flaw angles may cause the fractal feature of surface cracks to develop moderately and stably, not like two same flaw angles with greater or lesser fracture development degree.

4. Conclusions

Uniaxial compression tests on rock-like specimens containing two preexisting parallelogram flaws were carried out on a rock mechanics servocontrolled testing system. The flaw geometry was different from that in previous research, and the two flaws had varying inclination angles including $\alpha = \beta = 45^\circ$, $\alpha = 45 < \beta = 60^\circ$, $\alpha = 45 < \beta = 75^\circ$, $\alpha = \beta = 60^\circ$, $\alpha = 60 < \beta = 75^\circ$, and $\alpha = \beta = 75^\circ$, yet each flaw had the same area, short side, and height. The research investigated the initiation, propagation, coalescence, and failure modes of the cracks in rock-like specimens and the characteristics of surface cracks in ultimate failure modes of the specimens. Preexisting parallelogram flaws quite change the axial stress-strain curves and greatly influence the mechanical parameters of the specimens under uniaxial compression. Moreover, a dimensionless equivalent strength is applied to obtain a correlated formula between the equivalent strength ($\sigma_{JP}/\sigma_P$) and the influencing coefficient ($K$) of the flaw inclination angle. It also indicates that a larger difference between the two flaw inclination angles can reduce the peak strength and peak strain more sharply. For specimens containing two parallelogram flaws, the crack initiation stress and the second initiation stress are distinctly related to the flaw inclination angles, although the crack initiation stress presents a change trend generally similar to that of the crack second initiation stress with increasing flaw inclination angle. Most of the macro first cracks initiate from the middle part above the upper
inner tips of the two preexisting flaws and near the tips of the flaw with the smaller angle in each specimen. Moreover, the effect of the lower-angle flaw on the crack initiation position is great, and whether the two flaw inclination angles in a specimen are the same relatively affects the occurrence of tensile wing cracks. This study also reveals the important influence of flaw inclination angles in the specimen on its crack propagation behavior; it is easier for the lower-angle flaw to produce intact wing cracks or cracks first at the tips of the flaws, and secondary cracks are relatively numerous and complicated. Additionally, the cracks in the failed specimens from the experiment are a mixture of various crack types, and four modes of ultimate macroscopic failure morphology can be summarized. Meanwhile, the crack coalescence and failure modes, depending largely on the inclination angles of the two flaws in a single specimen, can be classified into three distinct types. Additionally, on the basis of analysis on the characteristics of surface cracks in ultimate failure modes of the specimens, we can know that the arch-like prefabricated flaws also present a big impact on the dip angle development of surface cracks in ultimate failure modes of the specimens and cause new cracks to evolve along the direction of the flaw inclination angle. Also, two different flaw angles may cause the fractal feature of surface cracks to develop moderately and stably, not like two same flaw angles with greater or lesser fracture development degree. These results can be used to better understand the cracking mechanism of two preexisting parallelogram flaws with different properties, which would provide some theoretical support for arch-like fracture development under the influence of coal mining.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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