Infrared Radiation Characterization of Damaged Coal Rupture Based on Stress Distribution and Energy

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ABSTRACT: As coal mine production enters the deep mining stage, the impact of coal and rock dynamic hazards is becoming more and more significant. And the coal and rock containing initial damage such as fractures are more susceptible to destabilization damage by disturbance. So, this paper takes coal containing macro-crack with different inclination angles as the research object and uses the RMT-150B rock mechanics system to carry out uniaxial loading rupture tests on the specimens. On this basis, the changes in infrared radiation on the surface are observed using an infrared thermal imaging camera, and it is analyzed and studied according to the stress distribution and energy change of the specimens. The results show that the strain ratio at crack closure after bearing the coal gradually increases with the increase in the macro-crack inclination. When the inclination angle is $0° < \alpha < 90°$, there are obvious low-temperature bands on the upper and lower sides after macro-crack closure. The variance of the infrared thermal image of the specimen can reflect its infrared radiation information more effectively and has a good correspondence with the stress−strain curve. With the increase in the specimen macro-crack inclination angle, the linear change of VIRT is more obvious, the rate of change gradually increases, and the inclination angle is the maximum at $90°$. The accumulated elastic strain energy $U_e$ is the main source of energy for the sudden change in infrared radiation generated during the bursting process that occurs when the specimen is damaged, and $U_e$ is linearly and positively correlated with the change in infrared radiation in front of the specimen peak. These will provide some experimental basis and theoretical guidance for the use of infrared radiation precursor characteristics to warn the damaged coal−rock dynamic disaster.

1. INTRODUCTION

At present, mine production is gradually entering the stage of deep resource extraction, and safety production will also face greater challenges, among which coal and rock dynamic disasters such as impact pressure and coal and gas protrusion are particularly prominent. The catastrophic process of coal and rock mass is often accompanied by the transfer and change of energy. From previous studies, it can be found that in the process of instability and failure of coal and rock mass, the energy stored in coal and rock mass will be released to the outside world through electromagnetic waves, sound, heat, and other means. Therefore, identification and analysis of these signals will help in mastering the disaster information of coal and rock mass, which has important guiding significance for early warning of coal and rock dynamic disasters and ensuring safe production.

In the early 1990s, Geng et al. introduced infrared remote sensing technology into rock mechanics. Later, Wu et al. performed infrared observation tests under loading on multiple mechanism models of tectonic earthquakes to expose infrared precursor information of tectonic earthquakes. Liu et al. introduced fractal, entropy, and statistical theories and proposed the use of characteristic roughness, entropy, and variance as quantitative analysis to describe the evolutionary characteristics of the infrared radiation temperature field during rock loading.

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Li et al.\textsuperscript{7} obtained the correlation between rock surface temperature and volumetric strain by observing rocks under uniaxial compression with a far-infrared thermal imaging camera. Zhang et al.\textsuperscript{8} used infrared thermography to monitor the whole process of granite roadway rockburst and analyzed the spatial evolution of infrared thermography to quantitatively characterize the temporal evolution of the temperature field during rockburst. For coal, Li et al.\textsuperscript{9} carried out uniaxial loading tests on coal in cylinders capable of withstanding certain pressures and photographed infrared information to analyze the infrared precursor information of gas−solid coupled coal rupture. Yin et al.\textsuperscript{10} carried out an experimental analysis of the infrared precursor characteristics of gas-bearing coal damage. Cheng et al.\textsuperscript{11} carried out uniaxial compression infrared experiments on flake containing precast cracked coal samples using an infrared monitoring system, and initially investigated the infrared radiation characteristics of the load damage process of coal samples containing precast cracks. Yang et al.\textsuperscript{12} carried out an experimental study of the internal infrared radiation temperature of composite coal during loaded rupture by means of specimen drilling. Tang et al.\textsuperscript{13} tested infrared radiation observation of load bearing damage processes on coals at different moisture contents and obtained the temperature effect of moisture on coal damage. Ma et al.\textsuperscript{14} investigated the effect of stress on the intensity and burst time of infrared radiation during coal fracture by uniaxially loading coal samples at different scales. The above previous studies have revealed that infrared radiation information can provide early-warning information on the process of coal or rock destabilization to damage, which is of great importance for disaster prevention and mitigation.

However, under practical engineering conditions, most coal have damage present, such as faults, laminations, joints, and macroscopic formations such as fractures, which increase the uncertainty of the occurrence of coal−rock dynamic hazards. Therefore, Li et al.\textsuperscript{15} investigated the effect of crack inclination on the physical properties of coal by conducting acoustic emission experiments with uniaxial loading on coal types with macroscopic cracks at different inclination angles. Li et al.\textsuperscript{16} carried out mechanical experiments and simulations on cracked shales with different dip angles to analyze the effect of crack dip angle on their damage process. Guo et al.\textsuperscript{17} carried out an experimental study on gabbro and provided a detailed description of the pattern of cracking produced by pre-cracking against damage at different dip angles. Cheng et al.\textsuperscript{18} investigated the mechanics, damage patterns and infrared radiation characteristics of sandstones with prefabricated fractures at different dips. Liu et al.\textsuperscript{19} proposed a new model for calculating the expansion path of winged cracks in rock containing cracks under compressive shear stress, and it is in agreement with the experimental results. Niu et al.\textsuperscript{20} investigated the time-varying principal frequency distribution characteristics during the rupture of intact as well as defective red sandstone using acoustic emission techniques and obtained that micro-shear rupture was the main cause of the final damage of the specimen. Xu et al.\textsuperscript{21} investigated the effect of single fracture inclination on the mechanical properties and energy storage characteristics of red sandstone, and obtained a damage intrinsic model for compression of specimens at different fracture inclination angles.

Previous tests on coal with prefabricated cracked specimens have studied the infrared characteristics of the coal less frequently, while the existing studies have mainly focused on flake coal samples, so further research is needed to reflect the infrared characteristics of coal during load bearing damage more realistically and accurately. In this paper, the bearing rupture tests under infrared observation were carried out on raw coal specimens (processed according to the International Standard for Rock Mechanics) with prefabricated cracks at different inclination angles under a fixed loading rate, based on which the infrared radiation characteristics were analyzed using AIRT, MIRT, and variance of infrared thermal image sequences. In order to study the influence of prefabricated crack inclination on primary coal and provide some theoretical support and experimental basis for early-warning of coal and rock mass dynamic disasters in engineering.

2. MATERIALS AND METHODS

2.1. Specimens Preparation. The specimens used for the test were selected from the same block of relatively intact raw coal in the Inner Mongolia region, and were cut and processed into rectangular specimens of 50 mm × 50 mm × 100 mm with an end-face error of no more than 0.02 mm. Then, the fabricated coal specimens were prefabricated with macro-crack, and cracks with inclination angles of $0^\circ$, $30^\circ$, $45^\circ$, $60^\circ$, and $90^\circ$ were cut out. The prefabricated macro-crack is 20 mm long and 2 mm wide. After constant temperature drying at 105 °C, wrap it with fresh-keeping film and cool it to room temperature for standby, as shown in Figure 1.

![Figure 1. Test specimen and sketch of coal specimen.](image)

2.2. Test System. Test system includes a loading system and an infrared monitoring system (Figure 2). The loading system is an RMT-150B electro-hydraulic servo tester, the maximum vertical force is 1000 kN, the deformation rate loading can be controlled in 0.0001−1 mm/s, and the accuracy is 3%. The infrared monitoring system uses Shanghai Thermal Imaging Technology Fotric225s model infrared camera, with infrared resolution of 320 × 240, the thermal sensitivity of 0.03 °C, the corresponding spectral band range of 8−12 μm, the measure-
ment temperature accuracy of ±2% when the ambient temperature is between 10 and 35 °C, the image acquisition of up to 30 Hz and the ability to monitor in real time and photograph infrared fluctuations within a defined range. And it can monitor and photograph in real time the specified range of infrared fluctuations.

2.3. Test Scheme. Three groups of 15 relatively homogeneous specimens are selected for grouping and numbering, and their physical parameters are shown in Table 1. In this test, displacement-controlled loading is adopted, and the loading rate is 0.005 mm/s. Infrared thermal imager is used for infrared monitoring at the frequency of 20 Hz/s. In order to reduce the influence of end effect, it is necessary to apply lubricant between the specimens and the indenter before loading. And to ensure the reliability of infrared thermal imager observation data and eliminate interference, experimental observation is carried out according to relevant experimental measures.13

Table 1. Physical Parameters

| specimen no. | macro-crack inclination (°) | specimen size (mm) | specimen mass (g) | loading rate (mm·s⁻¹) |
|--------------|-----------------------------|--------------------|-------------------|----------------------|
| NY-0-a       | 0                           | 49.67 × 49.98 × 99.31 | 289.21             | 0.005               |
| NY-30-a      | 30                          | 50.12 × 49.52 × 99.05 | 301.11             |                      |
| NY-45-a      | 45                          | 49.24 × 51.10 × 98.52 | 296.79             |                      |
| NY-60-a      | 60                          | 49.68 × 49.08 × 98.25 | 296.08             |                      |
| NY-90-a      | 90                          | 48.96 × 48.30 × 99.32 | 285.67             |                      |
| NY-0-b       | 0                           | 50.39 × 50.67 × 101.11 | 297.07             | 0.005               |
| NY-30-b      | 30                          | 48.87 × 49.74 × 100.05 | 286.86             |                      |
| NY-45-b      | 45                          | 51.05 × 48.85 × 100.47 | 280.45             |                      |
| NY-60-b      | 60                          | 50.31 × 50.22 × 100.37 | 288.69             |                      |
| NY-90-b      | 90                          | 51.31 × 50.27 × 99.04 | 298.25             |                      |
| NY-0-c       | 0                           | 50.82 × 50.58 × 100.34 | 289.54             | 0.005               |
| NY-30-c      | 30                          | 48.97 × 51.28 × 100.24 | 296.15             |                      |
| NY-45-c      | 45                          | 51.17 × 50.38 × 100.11 | 294.24             |                      |
| NY-60-c      | 60                          | 50.85 × 49.79 × 100.69 | 301.47             |                      |
| NY-90-c      | 90                          | 49.52 × 50.35 × 99.69 | 298.15             |                      |

the loading rate is 0.005 mm/s. Infrared thermal imager is used for infrared monitoring at the frequency of 20 Hz/s. In order to reduce the influence of end effect, it is necessary to apply lubricant between the specimens and the indenter before loading. And to ensure the reliability of infrared thermal imager observation data and eliminate interference, experimental observation is carried out according to relevant experimental measures.13 The specimens, the thermal imaging camera, and the thermometer are placed in the laboratory 24 h in advance so that the temperature of the specimen is consistent with the ambient temperature of the laboratory. The thermal imaging camera needs to be preheated for half an hour before the test starts and thermal gloves need to be worn to avoid human contact during the placement of the specimens. Besides close the doors, windows and lights during the test and do not allow people to move around.

3. ANALYSIS OF TEST RESULTS

Through the infrared radiation monitoring test of uniaxial loading to failure of coal specimens, which are prefabricated macro-cracks with different dip angles, the deformation and failure and the variation characteristics of infrared radiation are studied. Limited to space, select representative group a specimen's results for analysis.

3.1. Mechanical Properties of Macro-Cracked Specimens. Figure 3 shows the mechanical parameters of the specimens in group a. The destabilization process of the coal under uniaxial loading is roughly divided into the compression-density phase, the elastic deformation phase, the plastic yield deformation phase, and the damage phase.22,23 In the case of specimens containing prefabricated macro-crack, the elastic deformation phase does not develop continuously, with abnormal fluctuations occurring earlier in the loading interval due to the presence of cracks. Based on the test results, the loading process can be broadly divided into four stages as follows.

(1) The compaction stage: the primary pores in the coal are closed, and the coal deforms greatly under the action of small force.

(2) The elastic deformation stage: after compaction, the deformation law of coal specimen conforms to Hooke’s law, and its strain is positively correlated with stress. At the same time, the macro-crack with small angle gradually began to deform.

(3) The unrecoverable plastic deformation stage of crack development: with the increase of stress, due to the existence of macro-crack, after the elastic deformation reaches a certain degree, new cracks began to develop near the prefabricated macro-crack, accompanied by sound from time to time, and the stress–strain curve also fluctuates. At this time, the macro-crack with small angle has been basically closed, while those with large angles begin to have obvious deformation.
angles.

Figure 3. Mechanical parameters of specimens under different crack angles.

The uniaxial compressive strength and modulus of elasticity of the specimens are 10.68 MPa and 0.46 GPa, respectively, when the inclination angle $\alpha$ is 0°. With the increase of the inclination angle of the macro-crack, the compressive strength of the specimens is increased by 27.74, 66.57, 54.59, and 188.85% when $\alpha$ are 30°, 45°, 60°, and 90° respectively, and the modulus of elasticity are also increased to 1.36, 1.34, 1.01, and 1.81 GPa respectively. This is consistent with the results of experiments carried out by Li using briquette. These shows that macro-crack in the horizontal direction within the specimen have a significant effect on its uniaxial compressive capacity, significantly reducing its uniaxial compressive strength. As the dip angle of crack increases the compressive strength increases significantly and the modulus of elasticity also increases significantly.

3.2. Infrared Thermal Image Characteristics of Specimens. The temperature field distribution on the specimen surface changes in real time during the loading process, and is closely related to the loading process. Therefore, through the real-time observation of the whole process of specimen loading by infrared thermal imager, the infrared radiation law on the specimen surface can be monitored. In order to more intuitively reflect the temperature change on the surface of the specimen, as shown in Figure 4, it is the comparison effect of the infrared radiation image of the specimen and the failure form of coal.

When specimens contain prefabricated macro-crack, the difference in macro-crack inclination affects the damage morphology of the coal. The white oval area shown in Figure 4 identifies the location of the macro-crack, which is shown differently in the thermal image due to differences in camera angle and fracture morphology. When the thermal imaging camera is positioned in a fixed position during the test, the thermal imaging camera will show the infrared information of the test background when the position of the camera corresponds to the crack, so bright stripes will appear. While when the position of the camera does not correspond well, it may not be obvious or darker stripes will appear. At $\alpha = 0°$, the macro-crack is brightly colored and gradually closes with increasing pressure, and it basically closes completely at $0.5\varepsilon_p$; at $\alpha = 30°$, the macro-crack does not appear more obviously in the infrared thermal image, and the crack is basically closed at around $0.7\varepsilon_p$ according to the visible light observation; at $\alpha = 45°$, the macro-crack is not apparent in the infrared thermal image in the early stages, after which the crack can be found to close at around $0.75\varepsilon_p$ and a frictional effect occurs, leading to a brief anomalous band of high temperature at the crack; at $\alpha = 60°$, the macro-crack is black at the first stage and closes at around $0.8\varepsilon_p$ in the infrared thermal image; at $\alpha = 90°$, the macro-crack is brightly striped and the crack is not completely closed until it ruptures. That is, the strain ratio at macro-crack closure of the specimen increases with increasing inclination angle.

By observing the infrared thermal image, it can be found that when the macro-crack inclination angle is 0°, the crack development of the specimen is concentrated near the macro-crack, and mostly perpendicular to the macro-crack. This process is mainly in the form of splitting damage, and the black low temperature region can be observed in the infrared thermal image at the late stage of rupture, i.e., at the splitting damage. At the same time, when $\alpha > 0°$, high-temperature mutation anomalies are mostly generated near the macro-crack due to the friction in the specimen, and the resulting temperature anomalies are mostly generated near the macro-crack damage. However, when $\alpha < 90°$, clear blue-black cryogenic bands can be observed on the upper and lower sides of the crack during the bearing process, especially when the crack of 45° sample is closed and before the failure of 60° sample. As the macro-crack inclination increases, the damage type of the specimen changes from tensile splitting at 0° to a combination of shear and tensile damage, with both tensile damage and shear friction in the specimen, and the resulting temperature difference makes the splitting cooling on both sides of the crack more prominent. When the macro-crack tilts to 90°, the crack is almost not completely closed during the bearing process, and the specimen shows an overall warming trend at this time, and the infrared thermal image changes abruptly at the moment of specimen rupture instability.
Figure 4. Comparison diagram of infrared radiation evolution and fracture morphology of the sample.
The evolution of the infrared thermal image reflects the change in temperature distribution on the specimen surface. The variety of the macro-crack causes a change in its strain at the point of complete closure during the specimen bearing process, and overall the node of crack closure is gradually delayed as the inclination increases. Through infrared thermography, it can be found that the abnormal area of high temperature mostly occurs at the bursting area of the sample. This is because the mechanical energy of the external load is transformed into elastic energy and stored during the process of bearing to destruction of the coal; when the coal undergoes plastic deformation, the coal particles will undergo relative friction resulting in local heating. When loaded to the bearing limit of the coal, the coal destabilization rupture, the accumulated elastic energy is released, which is converted into kinetic energy of the broken coal and other forms of energy, and the friction effect of the broken coal burst process is the main reason for its sudden temperature change.

3.3. Infrared Radiation Intensity Change of Macro-Crack Coal Specimens. Based on previous studies, it has been found that the infrared radiation changes from bearing to destabilization of coal can be characterized and analyzed using the average infrared radiation temperature (AIRT), the maximum infrared radiation temperature (MIRT), and the variance of infrared thermal image (VIRT).

AIRT, that is, the average value of all infrared radiation intensity in each frame of the thermal imaging video, can more intuitively reflect the overall change in the temperature field of the specimen; the average infrared radiation temperature of the ith frame is

$$\text{AIRT}(i) = \frac{1}{L_x} \sum_{x=1}^{L_x} \frac{1}{L_y} \sum_{y=1}^{L_y} f_i(x, y)$$  \hspace{1cm} (1)

where $L_x$ is the maximum row of the infrared radiation matrix; $L_y$ is the maximum column of the infrared radiation matrix; and $f_i(x,y)$ is the infrared radiation matrix.

MIRT is the maximum value of infrared radiation intensity in each frame of the infrared thermal image video, which can more intuitively reflect the sudden change in temperature of the specimen during the bearing process, the larger the MIRT the more drastic the sudden change, the maximum infrared radiation temperature of the ith frame is

$$\text{MIRT}(i) = \max \left( \frac{1}{L_x} \sum_{x=1}^{L_x} \frac{1}{L_y} \sum_{y=1}^{L_y} f_i(x, y) \right)$$  \hspace{1cm} (2)

VIRT is the infrared radiation variance of each frame in the thermal image video of the specimen, it can portray the specimen temperature field divergence phenomenon, reflecting the degree of deviation from the mean value of its temperature field, the more obvious the divergence phenomenon, the greater the variance. The maximum infrared radiation temperature of the ith frame is

$$\text{VIRT}(i) = \frac{1}{L_x} \sum_{x=1}^{L_x} \frac{1}{L_y} \sum_{y=1}^{L_y} \left( f_i(x, y) - \text{AIRT}(i) \right)^2$$  \hspace{1cm} (3)

Figure 5 shows the change curves of stress, AIRT, MIRT, and VIRT of each specimen with loading time. It can be found that AIRT, MIRT, and VIRT have different description effects on the change of infrared radiation. Among them, AIRT has both heating and cooling areas in the infrared thermal image of the sample during the bearing process, resulting in small changes,
and even offset each other. Although the infrared thermal image can be described as a whole, the effect is poor. Secondly, there is a certain correlation between MIRT and stress curve. The sudden increase of MIRT can reflect the bearing state of the sample. But by comparison, The VIRT is more sensitive to infrared radiation information and can be more consistent with the stress curve. With the increase of inclination angle, the change trend of infrared radiation on the sample surface changes obviously, and the main mutation occurs near the stress limit. Further analysis of the infrared thermal image of variance revealed that when \( \alpha = 0^\circ \), VIRT is almost horizontal, but fluctuated more, especially when the stress curve was perturbed, because the specimen at this inclination angle is mainly splitting damage during the loading rupture, and the release of elastic potential energy and tensile damage cooled down together. When \( \alpha = 30^\circ \), VIRT is also almost horizontal, but the fluctuation is significantly reduced. At \( \alpha = 45^\circ \), VIRT fluctuates more strongly in the OA phase, with a more pronounced linear increase in the AB phase and an obvious sudden increase near the beginning of the plastic phase. At \( \alpha = 60^\circ \), VIRT increases significantly linearly in the OA and AB phases, with sudden fluctuations corresponding to the stress curve in the BC plastic phase. And at \( \alpha = 90^\circ \), VIRT increases almost linearly in the whole phase until the rupture when the sudden change occurs at rupture. As the macro-crack inclination increases, the infrared thermal image of VIRT becomes more stable and the warming trend with increasing load becomes apparent.

In addition, when \( \alpha \) is 0°, the specimen undergoes two linear elastic deformations. This is because the macro-crack angle of inclination is small, when the macro-crack is deformed and closed, which does not produce an inclined slip surface that immediately breaks the specimen. It can continue to carry the load until complete damage. As the angle of inclination increases, when the macro-crack is closed and the crack begins to expand, the appearance of the inclined slip surface makes it impossible for the specimen to continue to carry the load for a long time.

A linear fit to the prerupture mutation phase based on the VIRT of the specimen infrared thermal image sequence is shown in Figure 6. The overall variation in VIRT is found to be small when the macro-crack inclination is 0° and 30° (Table 2). A weak negative correlation is observed at 0°, while at 30°, a shift toward an increasing trend is observed, albeit a smaller magnitude. This is due to the fact that when the inclination angle is small, the coal is mainly affected by the tensile damage during loading damage and its surface infrared radiation changes fluctuate widely, causing its VIRT changes to be scattered. When the macro-crack inclination continues to increase, it gradually changes from tensile splitting to tensile and shear composite, and finally to shear bursting; the rate of change of VIRT increases significantly while its stability also gradually increases, of which the rate of change is greatest at an inclination of 90°. It can also be found that with the increase of the specimen macro-crack inclination, the rate of change of its infrared radiation VIRT is approximately positive correlation.

| Table 2. Regression Equations of VIRT under Various Angles |
|-----------------|-----------------|--------|
| macro-crack inclination (°) | relation equation | \( R^2 \) |
| 0 | \( y = -3.342 \times 10^{-3} x + 0.278 \) | 0.82 |
| 30 | \( y = 8.636 \times 10^{-3} x + 0.084 \) | 0.86 |
| 45 | \( y = 3.16 \times 10^{-3} x + 0.066 \) | 0.94 |
| 60 | \( y = 4.61 \times 10^{-3} x + 0.132 \) | 0.98 |
| 90 | \( y = 8.36 \times 10^{-3} x + 0.078 \) | 0.99 |

The damage to the specimens with macro-cracks mostly appears as typical single bevel shear damage, due to some friction between the top and low ends of the specimen and the indenter under uniaxial resulting in radial stresses at both ends of the specimen (i.e., end effect). But the specimens with a height-to-diameter ratio of 2:1 according to ISRM can ignore the end effect and are considered to be subjected to compressive stresses only. At the same time, the application of lubricant at both ends is the prepeak infrared radiation change, and \( \Delta T_m \) is the mean value of infrared radiation range, \( \Delta T \)

| Table 3. Experimental Results |
|-----------------|-----------------|--------|
| macro-crack inclination (°) | specimen no. | \( \Delta T_m \) (°C) | \( \Delta T_{max} \) (°C) |
| 0 | NY-0-a | 2.40 | 0.29 |
|  | NY-0-b | 2.76 | 0.34 |
|  | NY-0-c | 3.03 | 0.26 |
| 30 | NY-30-a | 3.73 | 0.50 |
|  | NY-30-b | 3.87 | 0.62 |
|  | NY-30-c | 3.72 | 0.59 |
| 45 | NY-45-a | 3.77 | 1.03 |
|  | NY-45-b | 3.91 | 1.24 |
|  | NY-45-c | 4.08 | 1.17 |
| 60 | NY-60-a | 3.92 | 0.84 |
|  | NY-60-b | 3.85 | 1.28 |
|  | NY-60-c | 4.03 | 1.03 |
| 90 | NY-90-a | 4.19 | 2.09 |
|  | NY-90-b | 4.26 | 1.58 |
|  | NY-90-c | 4.08 | 1.76 |

Figure 6. Regression analysis of VIRT.
of the sample before the test also achieves the effect of restraining the end effect. Therefore, the tensile crack of the sample occurs and expands to the low stress area mainly due to the Poisson effect. 21 When the macro-crack inclination is less than 90°, due to the existence of that, the two ends of it are the stress concentration area and the stress after bearing is much greater than other locations, which causes the macro-crack to close during the loading process in the course of the test. Meanwhile, the macro-crack ends are also near where the secondary cracks start to develop, and the stress-strain curve fluctuates during the test due to the closure of the macro-crack and the development of the cracks. These cracks are caused by both tensile and shear damage, with the more obvious tensile damage occurring in the specimens with 0° and 30° inclination angles, where there is a significant drop in the infrared image when the strain reach its limit. In the case of shear cracks, the friction caused by the resulting slip surface is one of the reasons for the increase in infrared radiation intensity on the specimen surface, which is more pronounced at inclination angles of 30°, 45°, and 60°. The stress distribution evolves from symmetrical to axisymmetrical as the inclination angle increases, until the crack becomes symmetrical again at an inclination angle of 90°. The comparison also reveals that high temperature anomalies in infrared radiation tend to occur in areas of high stress (Figure 8).

4.2. Influence of Energy Evolution on Infrared Radiation. According to the first law of thermodynamics, when the external force does work on coal and rock materials in a closed system, the input energy \( U_t \) of the external force is:

\[
U_t = U_d + U_e
\]  

where \( U_t \) is the total strain energy of coal and rock mass under stress and deformation, \( U_d \) is the dissipated energy in the process of coal and rock mass deformation, and \( U_e \) is the elastic strain energy stored in the process of coal and rock mass deformation.

Take a coal–rock unit for energy analysis, and the total strain energy absorbed and accumulated by the coal–rock unit can be expressed as:

\[
U_t = \int \sigma_i d\varepsilon_i + \int \sigma_2 d\varepsilon_2 + \int \sigma_3 d\varepsilon_3
\]

(5)

where \( \sigma_1, \sigma_2, \) and \( \sigma_3 \) are the principal stress of coal–rock mass unit; \( \varepsilon_1, \varepsilon_2, \) and \( \varepsilon_3 \) are the principal strain corresponding to principal stress.

Under uniaxial loading, \( \sigma_2 \) and \( \sigma_3 \) are zero; therefore, the total strain energy and elastic strain energy of coal–rock unit can be simplified as:

\[
U_t = \int \sigma_i d\varepsilon_i = \sum_{i=0}^{n} \frac{1}{2} (\sigma_{i+1} + \sigma_{i}) (\varepsilon_{i+1} - \varepsilon_{i})
\]

(6)

\[
U_e = \frac{1}{2} \sigma_i \varepsilon_i = \frac{\sigma_i^2}{2E_u}
\]

(7)

where \( \sigma_i \) and \( \varepsilon_i \) are, respectively, the corresponding stress and strain values on the main stress–strain curve; \( E_u \) is the unloading elastic modulus; and the elastic modulus \( E_0 \) can be used to approximately replace \( E_u \) in calculation. 24,25

From eqs 1234, the dissipated strain energy of coal–rock unit is:
\[ U_d = \int \sigma_1 d\varepsilon_1 - \frac{1}{2E_0} \sigma_1^2 \]  
(8)

In addition, the percentage of dissipated energy is:

\[ R_d = \frac{U_d}{U_t} \]  
(9)

It can be seen from Figure 9 that in the compaction stage, at the initial stage of loading, \( U_o, U_e, \) and \( U_d \) do not change significantly with the increase in the stress–strain ratio because the work done by external forces at this stage mainly acts on the closure of micro-crack of the sample. There is no energy storage of elastic deformation and no energy dissipation caused by sample damage. In the period of elastic deformation, \( U_e \) increases synchronously with the increase of \( U_t \). At this stage, the work done by external forces is mostly accumulated in the form of elastic deformation. Then it enters the stage of unrecoverable plastic deformation, which is the main growth period of \( U_d \). At this time, in addition to the initial crack, the secondary cracks begin to develop and expand, accompanied by abnormal noise from time to time, and the infrared thermal image also has abnormal fluctuations. In the final stage of rapid crack development and penetration, \( U_e \) drops rapidly, and the sample is rapidly unstable and damaged (Table 4). At this time, the infrared radiation on the sample surface surges. The linear correlation between the total strain energy \( U_t \), and the change in infrared radiation in front of the peak coincides with the fact that the increase in infrared radiation is mainly due to the work done on the system by
external forces (Figure 10). However, there is a certain amount of energy released early in the process due to the presence of energy dissipation, resulting in a poor correlation, which is also the main reason for the anomalies or mutations in the MIRT and VIRT curves in Figure 4. In comparison, the elastic strain energy $U_e$ is more closely related to it. From the side, reflecting the main source of infrared radiation of the specimen is the accumulated elastic strain energy.

5. CONCLUSIONS

(1) The angle of inclination of the macro-crack affects the closure of the macro-crack after the coal is loaded. As the macro-crack inclination increases, the strain ratio for its closure increases. When the inclination angle is $0^\circ < \alpha < 90^\circ$, there will be obvious low-temperature stripes at the top and bottom of the macro-crack after it closes due to the Poisson effect, producing tensile damage. Until the coal is destabilized and ruptured a high temperature anomaly zone appears near the macro-crack.

(2) Compared with AIRT, MIRT, and VIRT, the variance of the infrared thermal image of the specimen can reflect the infrared radiation information more effectively and corresponds better to the stress–strain curve. As the macro-crack angle of the specimen increases, the linear variation of VIRT becomes more obvious and stable, and the rate of change increases gradually, reaching a maximum at an angle of $90^\circ$.

(3) As the inclination angle increases, the stress distribution changes from axisymmetric to centrosymmetric to axisymmetric. Areas of stress concentration are more likely to result in the development of secondary cracks, which in turn cause changes in infrared radiation. Therefor the high stress concentration areas of the specimen are therefore areas where sudden IR changes in the coal are more likely to occur and these areas need to be monitored.

(4) The elastic strain energy, $U_e$, is linearly related to the infrared radiation change in front of the specimen peak, and the accumulation of $U_e$ is the main source of energy for the infrared radiation change during the damage that occurs when the specimen is destabilized. The dissipation energy, on the other hand, is the main influencing factor for the sudden, anomalous infrared changes that occur during the process. Therefore, the macro-crack inclination has a corresponding effect on the infrared radiation of the specimen while affecting the energy change.

### Table 4. Peak Energy of Specimens at Each Crack Dip

| macro-crack inclination (°) | specimen no. | $U_t$ (MJ/cm$^3$) | $U_e$ (MJ/cm$^3$) | $U_d$ (MJ/cm$^3$) | $R_d$ (%) |
|-----------------------------|--------------|-------------------|-------------------|-------------------|-----------|
| 0                           | NY-0-a       | 100.61            | 45.46             | 55.15             | 54.82     |
|                             | NY-0-b       | 120.54            | 61.20             | 59.34             | 49.23     |
|                             | NY-0-c       | 97.43             | 46.08             | 51.35             | 52.70     |
| 30                          | NY-30-a      | 88.97             | 49.10             | 39.87             | 44.81     |
|                             | NY-30-b      | 85.26             | 45.34             | 39.92             | 46.82     |
|                             | NY-30-c      | 102.47            | 51.07             | 51.4              | 50.16     |
| 45                          | NY-45-a      | 142.27            | 98.16             | 44.11             | 31.00     |
|                             | NY-45-b      | 135.66            | 88.27             | 47.39             | 34.93     |
|                             | NY-45-c      | 137.71            | 82.64             | 55.07             | 39.99     |
| 60                          | NY-60-a      | 172.40            | 102.18            | 70.22             | 40.73     |
|                             | NY-60-b      | 181.24            | 98.34             | 82.9              | 45.74     |
|                             | NY-60-c      | 164.29            | 85.17             | 79.12             | 48.16     |
| 90                          | NY-90-a      | 264.07            | 143.81            | 120.26            | 45.54     |
|                             | NY-90-b      | 251.33            | 138.78            | 112.55            | 44.78     |
|                             | NY-90-c      | 227.18            | 137.66            | 89.52             | 39.40     |

Figure 10. Relationship between energy and infrared temperature difference before peak.

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Notes
The authors declare no competing financial interest.

The data used to support the findings of this study were supplied by author under license and so cannot be made freely available. Requests for access to these data should be made to Dr. Fan Li (Contact ID: lifan2652218@163.com).

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