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Research on quantitative identification of infrared characteristics of progressive failure of bolted roadway surrounding rock

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ABSTRACT

By means of uniaxial loading and thermal infrared imaging technology, this paper makes physical model test on progressive failure of bolted roadway surrounding rock. The results indicate that: (I) before stress peak, the infrared radiation temperature (IRT) on surface of roadway surrounding rock rise non-synchronously, and the IRT on stress concentration and shear fracture areas is higher and intensive than that on stress relaxation and tensile fracture areas; (II) the IRT on various parts of model such as roof, walls, floor and angles, changes non-synchronously, which can be reflected through the change rate of IRT to identify the progressive failure of roadway surrounding rock; (Ⅲ) two kinds of infrared precursors can be obtained corresponding to the progressive failure areas of roadway surrounding rock respectively. The bolted areas are determined from the change ratios of TIR temperature of the various areas of the bolted surrounding rocks, which provides a theoretical basis for designing parameter of bolt supporting. It is also verified that the thermal infrared imaging technology can be used to study the mechanism of bolt supporting and supervise the stability of roadway surrounding rock.

Key words: Infrared radiation; bolt support; stress concentration; stress relaxation; infrared precursor

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INTRODUCTION

Coal is the main energy in China, accounting for more than 70% in the production of disposable energy and consumption structure for many years. China is also the world's largest coal producer and consumer. A highly effective and safe coal mining technology is critical to ensure coal production. However, the technology level and security situation of China's coal production are not optimistic with all kinds of accidents occurring happening occasionally. Threats from mine's roof disasters are serious, which currently occur most frequently among all these accidents, with the largest number of deaths [1]. As the conditions of the coal seam are complicated, the rock mass is relatively weak and the joint is presented with fracture development, roof accidents of coal mine are the majority in those of the mine. Roof accidents account for more than one third in mine accidents, and roadway roof accidents account for 80% of roof accidents. The death toll reached 890 in roof accidents of coal mine in 2010 which caused huge economic losses. For example, particularly significant roof accident that occurred in Tashan mine of Datong Mining Group killed 11 people, and made the collapsed range of the roadway up to 47m. According to the statistics, the number of deaths in coal mine industry was 6478 in 1999, of which the number of deaths who were killed by roof accidents was 1997, accounting for 30.8%; the number of deaths in coal mine industry was 5823 in 2000, of which the number of deaths who were killed by roof accidents was 1546, accounting for 26.5%; Roof accident was mainly caused by backward coal mine roadway supporting technology, so safely, reasonably and effectively controlling roadway surrounding rock is the problem that needs to be solved urgently.

Coal bolt supporting has an obvious drawback: the damage and instability of the roof are unexpected, and the range of the roof fall is relatively large; due to the concealment of the activities of roadway surrounding rock supported by bolt supporting, there are generally no obvious warnings from the damage and instability of the surrounding rock, and it is not easy to be conceived by people, making the damage unexpected. Currently, there are no effective monitoring and detection methods and equipment to detect the construction quality and the actual working status of the bolt, so the hidden risks of roof fall in the roadway cannot be found timely, which causes the frequent happening of roof fall accidents in roadway supported by bolt supporting. According to statistics, in recent years, the death tolls which were caused by a variety of accidents in state-owned coal mine are up to 6,000 per year, in which the death tolls which were caused by roof accidents were nearly 2,000, resulting in extremely bad social impact and huge economic losses.

Because of the complexity, variability and uncertainty of the geological conditions of the roadway in the coal mine, when designing the supporting of the roadway supported by bolt supporting, it is difficult to ensure scientific and rational technology parameters, resulting in the fact that insufficient supporting of partial roadway makes the surrounding rock instable and damaged, while over 60% roadway which has excess supporting wastes substantial materials [2]. To completely change this passive situation, we must continue to study the mechanism of coal roadway bolt, ensuring scientific and rational technology parameters of bolt supporting; actively seek new methods to monitor the stability of roadway surrounding rock, to take timely and effective technical measures to prevent the damage and deformation of the roadway [3].

Therefore, we must continue to further study the mechanism of coal roadway bolt, ensure scientific and rational technology parameters of bolt supporting, select safe and reliable supporting methods, determine economic and rational supporting parameters and practical and efficient construction technology, actively seek new methods to monitor the stability of roadway surrounding rock, to take timely and effective technical measures to prevent roof caving and the damage of the roadway.

The infrared remote sensing technology provides a new idea for us to study the physical deformation process of the interaction between surrounding rock and bolt. Infrared remote sensing technology has been widely applied and played a significant role in industrial measurement, military reconnaissance, resource exploration, and research on volcanic and seismic activity. In the past decade, scholars at home and broad applied remote sensing technology to study the process of the stress in the field of rock, and made a lot of meaningful results.

In recent years, infrared technology has been applied to the study field of the mechanic characteristics and catastrophe of coal, rock, and concrete, steel, etc [4-13]. In the early 1990s, through observing and analyzing seismic flash, rising temperature on the earthquake ground and abnormal satellite infrared phenomenon before the earthquake, Cui Chengyu et al. [6] conducted an experiment on the electromagnetic radiation remote sensing under uniaxial compression and found the infrared radiation temperature of the rock, radiation intensity of infrared spectroscopy and that thermal infrared image changed with rock stress, visible light pulse signals appeared momentarily with rock fracture. Wu Lixin et al. [8] carried out an experiment on infrared detection of the pressed coal rocks and found three types of precursory information on the damage of the coal rocks. Through the studies in laboratory, An Liqian and Zhang Yongjun et al. [10, 11] found that in the process of the interaction between bolt and surrounding rock, surrounding rock and bolt will produce different intensities of infrared radiation and the changes of the intensities of infrared radiation are closely related to the loading conditions and deformation and fracture processes of the surrounding rock. Therefore, combining with the actual geological conditions of roadway in Lu'an Mining Group, the distribution rules of bolt supporting are studied through the infrared radiation detection, which provides new method for working area and the mechanism of bolt supporting.

GEOLOGICAL CONDITIONS OF ROADWAY

The coal seam and geological condition are shown in Table 1. Roadway drilling is in 3 #coal seam, whose average thickness is 6.05 m; roadway is 455m deep, 4m wide, 3 m high, with the inter-row spacing of the bolt of 0.8 m. Five full-length resin anchors and steel bolts with screw thread with the diameter of 20 mm and length of 2.4 m are arranged in the roof, with the bolts in each row connected with the W-shaped steel belt; four resin anchors and round steel bolts with the diameter of 16 mm and length of 2 m are arranged in the walls, with the bolts connected by the rods.

Table 1: Geological conditions of roadway project

Seam number	Lithology	Thickness /m	Compressive strength /Mpa	Features of lithology
1	Siltstone	2.5	53.6	Grey and dark Siltstone
2	Sandstone	4.5	60.3	Composed by fine sandstone and medium sandstone
3	Sandy mudstone	4.4	42.3	Dark and grey mudstone, containing quartz sandstone
4	Coal	6.05	13.3	hard and the developed joints
5	Sandstone	3.03	48.5	Mid-fine grained sandstone
6	Carbonaceous mudstone	1.7	32.5	dark and grey mudstone

EXPERIMENTAL INSTRUMENTS AND METHOD

The simulated conditions of physical simulation experiments is the S1-5 roadway gate of Changcun mine of Lu'an Mining Group, with roadway's depth of 455-475m, average thickness of the coal seam of 6.05 m, the inclination of 3-6°, uniaxial compressive strength of the coal seam of 13.3Mpa; immediate roof of coal seam is dark and gray mudstone whose thickness is 4.4m, and uniaxial compressive strength is 51.3MPa; main roof is composed by fine sandstone and medium sandstone, whose thickness is 4.5m, uniaxial compressive strength is 60.3MPa; grey and dark siltstone or mudstone whose thickness is 2.5 m is above the main roof with uniaxial compressive strength of 50 ~ 60MPa; direct floor is mid-fine grained sandstone, whose average thickness is 3.03m, with uniaxial compressive strength of 40MPa; mudstone is below, with an average thickness of 1.7m.

The size of the section of the simulated roadway is 4m × 3.2m. Parameters of on-site supporting are as follows: in each row of the roof, 5 bolts are arranged evenly whose spacing is 1m, length is 2.5 m, angle of the angle bolt is 30 °, and strength of the bolt is 150-200kN; in each row of the walls, there are four bolts whose spacing is 0.8m, length is 2 m, row spacing of bolt is 0.9m, and strength of the bolt is 80kN.

As calculated, similarity ratio of the volume of the model is 1.47. If the ratio of the geometrical similarity is 50, the similarity ratio of the stress should be 74. As strength of the rock mass is much smaller than that of the rock, and test values of the strength of the rock has size effect, if coefficient of rock integrity is 0.3 and the coefficient of size effect is 0.25, then the similarity ratio of the strength in this simulation experiment is 20. Gypsum and cement are selected as cementing materials, sand as the aggregates, 10A fuse to simulate rib bolt, Φ1mm thin copper wire as roof bolt, and anchoring agent is mixed with 914 glue and calcium carbonate and water. Strength of the made rock and parameters of the similarity ratio are shown in Table 2. Similar materials with different strengths are used to simulate different types of rock mass.

Table 2: Similar material matching and mechanics parameters

Rock stratum	E/MPa	sand: cement: gypsum: sawdust: water
Third stratum	52	13: 6.5: 1: 1: 1
Second stratum	60	13: 8: 1: 1: 1
First stratum	50	13: 6: 1: 1: 1
Coal seam	13	13: 0.5: 1: 1:1
Floor seam	40	13: 3: 1: 1: 1

Size of the similar model is 40cm × 40cm × 10cm and size of the model roadway is 8cm × 6cm. Shimadzu EHG-UG500KN digital hydraulic server is used as the uniaxial loading device whose maximum static load is 750KN and load accuracy is within 0.5%; TVS-8100MK Ⅱ thermal infrared imager is used as infrared detection device, whose temperature sensitivity is 0.025 ℃, speed of image acquisition is 50 frames / second, and measurement wavelength is 3.6 ~ 4.6μm.

Setting the thermal infrared imager in the place which is about 1m far from the model, recording the changes of the infrared radiation temperature of the progressive failure of the model and then the phase displacement of the roadway surrounding rock can be obtained by drawing the deformation of the grid lines in the roadway surface, as shown in Fig.1.

Uniform velocity is taken as the velocity mode, with the rate of 8.33E-03mm/sec. In order to study the relation between thermal infrared images and deformation, the rate of their sampling is designed equally, i.e., 1 time/ s, and is also recorded at the same time. Wet curtains are hung around the experiment machine to reduce the environmental effects on the infrared radiation of the models.

Fig.1: TIR detection during uniaxial loading of the bolted roadway samples

RESULTS AND DISCUSSION

Deformation of the bolted roadway: Fig. 2 shows the load-stroke diagram of the bolted roadway. At the beginning of loading (section AB), the load-stroke curve has a steadily increasing gradient due to the closure of pre-existing cracks and micropores in the model. Then the curve is approximately linear during the elastic deformation stage (section BC). In this stage, the roadway keeps stable, and no big cracks grow to appearance. When the load reaches about 86% (point C, P=12.9kN) of the peak, the gradient decreases (section CD), which is regarded as a manifestation of new cracks developing and the model is approaching the post-peak region. The perfoliate fractures generate when load reaches the peak. The bearing capacity of sample decreases rapidly after peak. When the load descends about 4.2kN, the descending gradient decreases. The residual strength of sample comes from the interaction between bolts and rock. The experiment results show that the installation of bolts could effectively enhance the residual strength of the roadway. In this stage, many cracks in model grow wide and long, parts of roof falling, the sides of roadway bulging out, many large cracks appearing in the roadway.

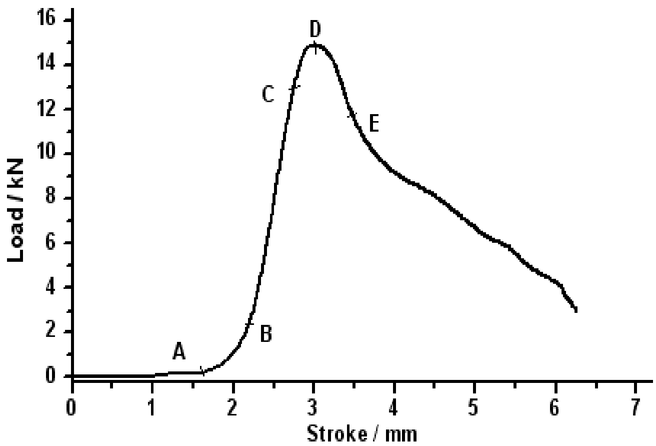


Fig.2: Load-stroke diagrams of the bolted roadway

Characteristic of TIR radiation images of the bolted roadway: The TIR radiation detection indicated, as illustrated in Fig. 3 that the overall surface TIR temperature (TIRT) changes with loading and model deformation. At the beginning of loading, surface TIR temperature decreased during the compression of the pre-existing micropores in the model. Then the TIRT increased very slowly. The increment was 0.04℃ when the micropores were compacted, as shown in Fig. 3 (a). During the elastic deformation stage (t=126-450s). The TIRT increased approximately linear. The TIRT in the bolted range increased faster and higher than that in other parts of the model. In this stage, the average TIRT increment of overall model was 0.17℃, the bolted range 0.21℃, the roof corner 0.24℃,and the floor corner 0.23℃, as shown in Fig. 3 (b).

During the plastic deformation, the model TIRT increased more rapidly. The TIRT of roadway circumference increased more rapidly and higher. In this stage, the average TIRT increment of overall model was 0.45℃, the bolted range 0.67℃, the roof corner 0.75℃, and the floor corner 0.52℃, as shown in Fig. 3 (c). With the failure of the sample, the TIRT descends rapidly, and the decrement was 0.5℃, as shown in Fig. 3 (d).

The TIRT changed non-synchronously in different ranges such as the roof, floor, wall, corners and bolted ranges. The reason was that the rock strength increased and stability of the roadway is improved after bolting. Furthermore, the TIRT decreased rapidly with the generation of every large crack. So, the interaction range of bolt and rock might be determined with IR technology. The new method of TIR imaging would be proved to be effective for the observation of roadway stability and broken area under mine pressure.

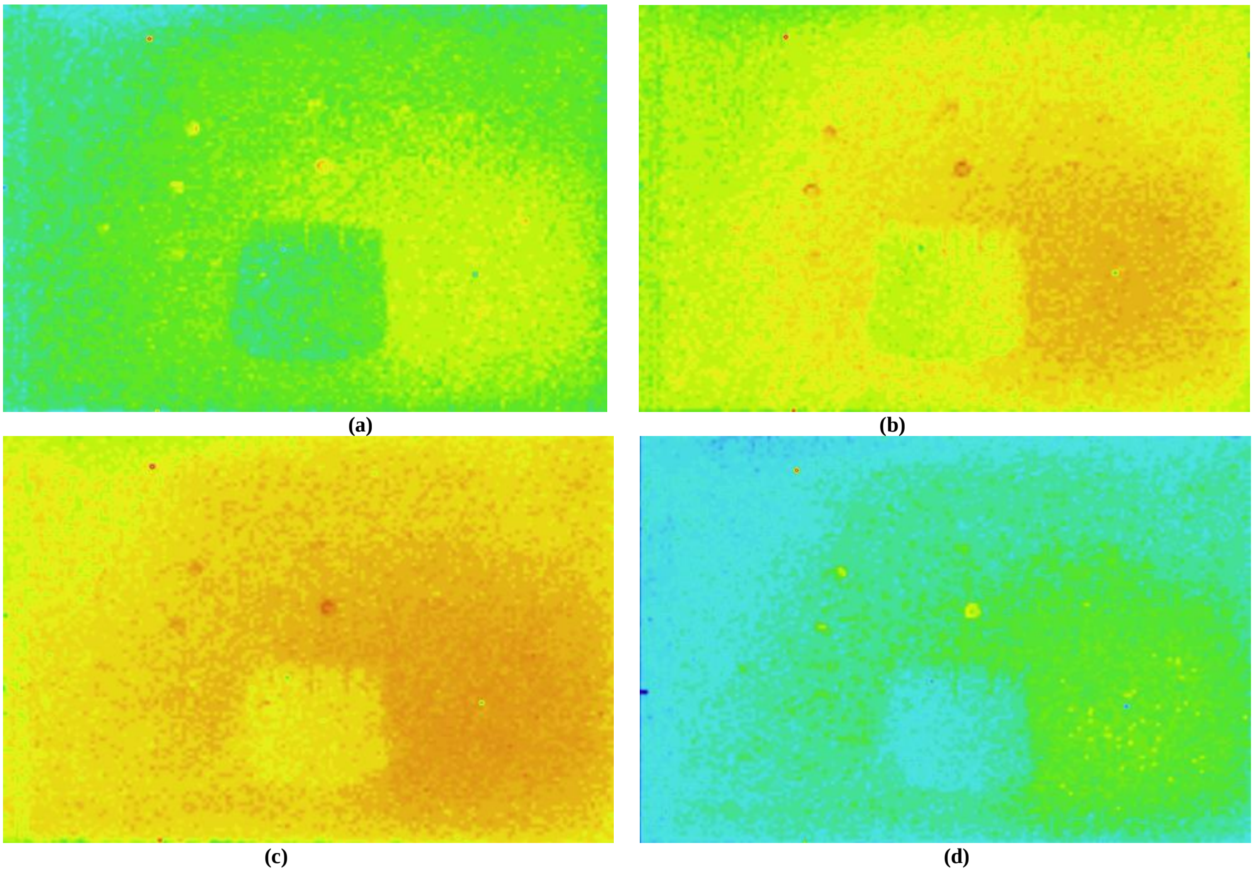


Fig. 3: The changing surface TIR radiation of uniaxially loaded bolted roadway. (a) 126s (P=4.78KN), (b) 450s (P=19.2KN), (c)1438s(P=40.54KN), (d) 1440s (after load peak)

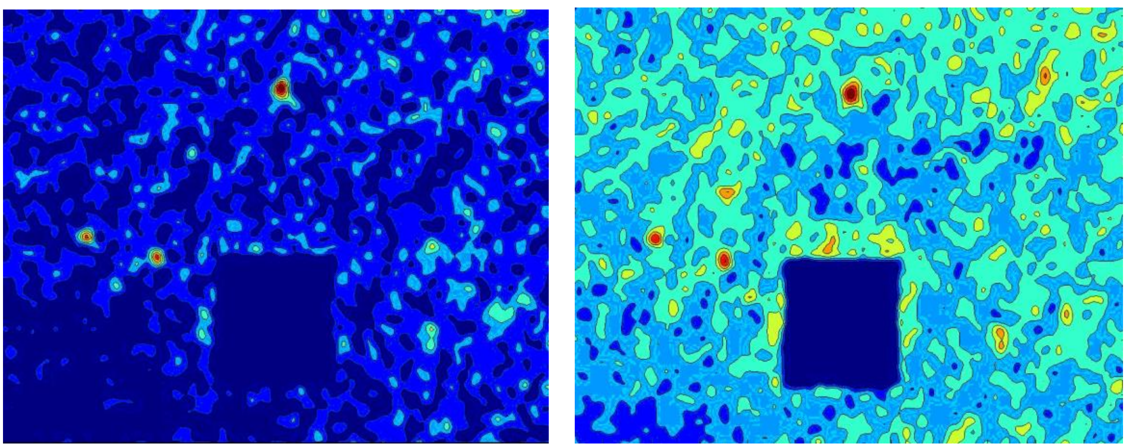
Quantitative identification of infrared radiation abnormal characteristics of roadways: It can be known from the thermoelasticity that, in the elastic stage, the temperature declines in the tensile stress area, while it rises in the compressive stress area. When reflected to the infrared thermogram of roadway surrounding rock, it can be seen that, before the peak stress, the place where infrared radiation temperature rises corresponds to the compression area, and the place where infrared radiation temperature declines corresponds to the tension area. It was found from the experiment that infrared radiation temperature of the shear area is higher than that of other areas, and its temperature rises more rapidly, so the changes of infrared radiation temperature correspond to the gradual damage areas of roadway surrounding rock, This paper initially extracts the interaction area between bolt and surrounding rock, according to the variations of the increments of infrared radiation temperature in different areas of the surrounding rock. For non-anchor roadway surrounding rock, it can be considered that the area where the continuous changes of infrared radiation temperature are consistent belongs to the same strain area, which is called isothermal area of infrared radiation. It can help carry out qualitative and quantitative analysis of the strain state.

Currently, the difficulty with which the infrared technology is used for gradual damage of the rock lies in: with the complexity of the damage mechanism of the solid and unpredictability of the damage position, the captured infrared thermal image may not reflect the deformation or damage process of the solid. Through studying the reason, it is found that the infrared radiation energy during solid deformation and damage is the sum of radiant energy in different wave bands with different intensities, and the infrared thermal images can only record the instantaneous infrared radiation temperature, so it needs to carry out secondary processing and development for the data of infrared thermal image.

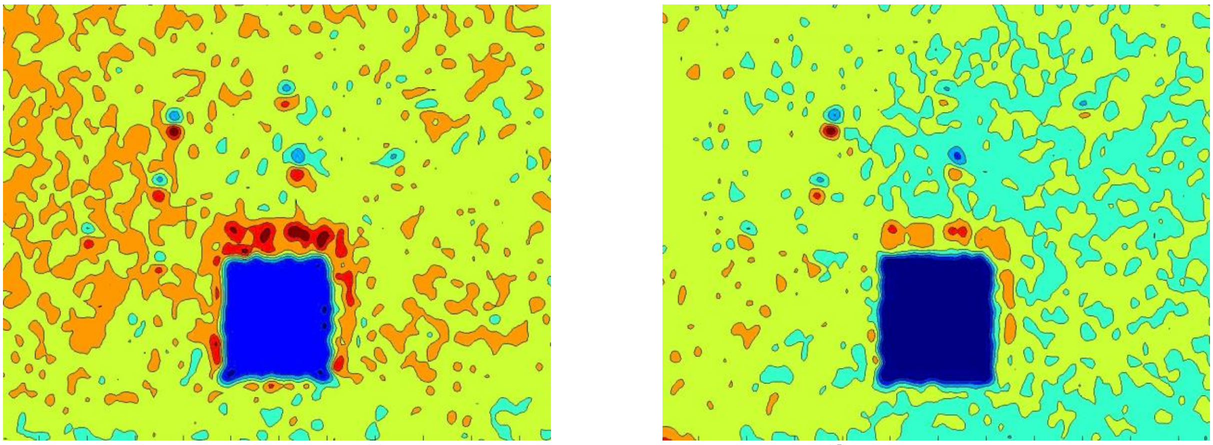
This paper firstly analyzes the characteristics of data record information of infrared thermal image instrument, and extracts the data of infrared radiation temperature through the designed and prepared program, then saves these data in the form of matrix, which can achieve universal processing; secondly, calculates the strains of various parts of non-anchor roadway surrounding rock, and combines with the original matrix of the initial position to carry out the processing, namely, trace and locate all areas of roadway surrounding rock to obtain distribution of the infrared radiation temperature field at any time in the process of deformation of roadway surrounding rock; and then subtract the data to obtain the variation of infrared radiation temperature of the roadway surrounding rock in the process of deformation; finally, carry out interpolation and fitting analysis for the subtracted data to obtain variation rules of the infrared radiation temperature of various areas of non-anchor roadway surrounding rock.

After making the above-mentioned processing on Fig. 3 and the initial infrared radiation image respectively, we can obtain isothermal diagram of infrared radiation of bolted roadway surrounding rock, where the central dark blue area indicates the roadway; the areas with different colors around the roadway reflects the deformation and progressive damage of roadway surrounding rock. The red area represents that the temperature rises, and that the darker the red area is, the higher the temperature is; the blue area represents that the temperature declines, and that the darker the blue line is, the lower the temperature is; as shown in Fig.4 (a), (b), (c) and (d). It can be seen that, as the load increases, the variation rules of infrared radiation temperature in various areas, visually reflects the evolution of the crack generation area, stress relaxation area and stress concentration area, visually reflects redistribution process of the stress of the roadway surrounding rock under the load, and also visually reflects the infrared radiation abnormal feature that is appeared with macroscopic crack in the gradual damage of roadway surrounding rock. The iso-TIRT regions were the approximately elliptical ranges where the bolt was located at the centre. With the loading increment, the regions of iso-TIRT enlarged, and the TIRT rose. The TIRT of outer iso-TIRT region was lower than that of the inner region and the TIRT of the benmost iso-TIRT region was the maximum.

Fig. 4 shows the distribution of change of the infrared temperature field in different areas of roadway surrounding rock. The yellow area around the roadway is interaction area between the bolt and surrounding rock, which can be regarded as the surrounding rock area within the bolts, and its internal dark red tapered area corresponds to the position of the bolt end, indicating the scope and shape of stress concentration area of the bolt end. The rising range of the infrared radiation temperature of the roof is large, indicating that the control effect of the bolt for the roof is obvious. The discontinuous changes of the temperature in other areas in the figure reflect the process of crack development and production, and also reflect the non-linear process of changes of the stress of roadway surrounding rock before and after bolt supporting. It can be seen from Fig. 4 (c) that the loading bearing of the bolted roadway increases much and the corresponding stress and strain are improved for keep the roadway more stable. In the interaction between bolt and rock, the TIR radiation strength of the bolt is different from that of rock. In the area of the interaction, the TIR radiates more intense than that of the other parts, and the TIRT is higher than that of the other parts. So the range of interaction between bolt and rock is determined through the analysis of the TIRT increment distribution of different parts.



(a) **(b)**

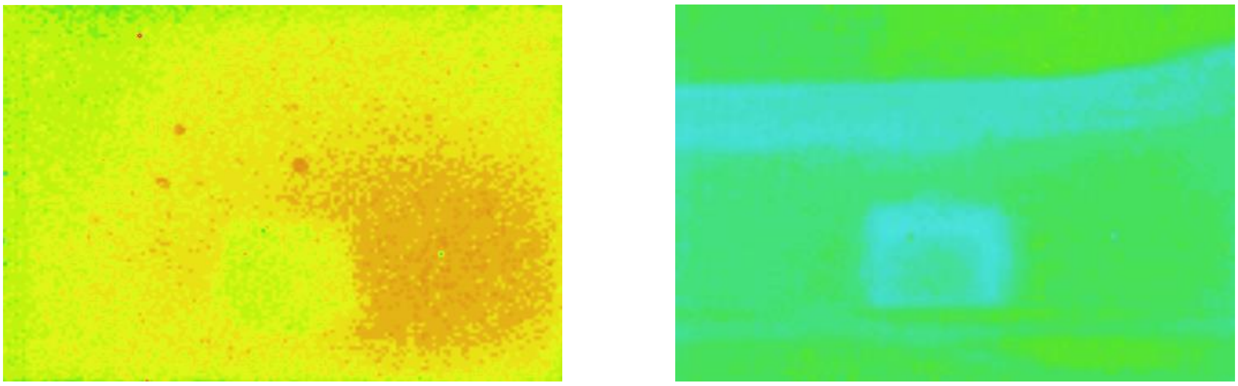


(c) **(d)**

Fig.4: The iso-TIRT regions of the uniaxially loaded bolted roadway (a)126s(P=4.78KN), (b)450s(P=19.2KN), (c)1438s(P=40.54KN), (d)1440s (after loading)

Infrared precursors of the bolted roadways: There always appears the phenomenon that infrared radiation temperature rises and declines rapidly when the whole model is instable; how to extract information on the infrared precursor to the crack becomes the key to determine whether the rock will be damaged. It is found that with the increase of the strain energy, the model enters into the plastic deformation phase from the elastic phase, presenting irreversible energy dissipation; and variations of infrared radiation temperature can reflect the process of the dissipation, and can also be affected by the material strength, deformability and developmental expansion generated by the cracks and other factors. Through the preliminary analysis, the increasing rising of infrared radiation temperature is mainly controlled by strain state of the surrounding rock, especially the shearing, combined with the rock strength theory, we regard the area where the temperature in the shear area continuously rises as the infrared heating precursor. On the other hand, tensile stress of the surrounding rock is comparatively small, near to the size of an order of magnitude, so, the resulting tensile strain is much smaller, when the corresponding tensile strain energy can reflect the changes of infrared radiation temperature, this small difference reaches the extent to which the current infrared thermal imager cannot detect the accuracy. so combined with characteristics of the strain, we can regard the constant-temperature area of infrared radiation in particular area as precursor to the infrared constant-temperature, and the improvement of precursor information needs to be further studied.

In the experiment, we obtain two kinds of infrared precursors to the crack of roadway, one is precursor to the continuous heating area of the infrared radiation, and the other is precursor to constant-temperature area of infrared radiation temperature. Fig. 5 showed that TIR image precursors could be classified as TIRT increment region and TIRT constant region. The TIR images precursors of bolted roadways failure were anomaly of TIRT fields of TIR images before the rocks fracture. The TIRT fields changed with not only the increase of elastic deformation energy but also the irreversible damage. In the process, the heat supply and the change in shape and position of rock volume elements which were the energy source for the plastic strain hardening and micro-crack formation in roadways led to the continuous growth of the micro-cracks dispersed in surrounding rock, which develop gradually from disorderly to orderly and form macro-cracks. Macro-cracks in turn concentrated in certain direction and finally form large cracks that lead to the integral instability. The TIRT increment region represented the compression-shear friction effect, and TIRT constant region represented the tensile-shear effect and tensile failure.



(a) **(b)**

Fig. 5：The TIR precursors of bolted roadways failure: (a) TIRT increment region, (b) TIRT constant region

CONCLUSION

From the TIR image variation with deformation and fracture of roadway during the loading process and from the analysis of the TIR precursors before the moment of fracturing and failure, the following conclusions were also discovered.

1. The temporal sequential features of the TIR radiation in the process of loading showed different staged characteristics in the roadway.
2. The TIR radiation was stronger in the location of stress concentration and bolted ranges than that in the location of stress relaxation, and the TIR of different parts radiated non-uniformly in the different stages of damage process.
3. The interaction ranges of bolt and surroundings rocks were determined preliminarily according to analysis of the TIRT increment distribution after the TIR image information extracting, strain analysis, TIR image subtraction, interpolation and fitting of TIR increment.
4. The TIR-anomaly characteristics of the samples surfaces reflected the features of test samples deformation and failure, and the TIR-anomaly appeared at the location of the stress concentration and fractures. TIR image precursors could be classified as TIRT increment region and TIRT constant region. The TIRT increment region represented the compression-shear friction effect, and TIRT constant region represented the tensile-shear effect and tensile failure.

The TIR radiation detection technology has a broad prosperity in the field of mining engineering, underground engineering and side slope engineering.

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