

Mechanism study on subcritical crack growth of flabby and intricate ore rock

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Abstract: Double torsion specimens were applied to study the subcritical crack growth of flabby and intricate ore in Jinchuan Mine. The relation between the subcritical crack velocity v and the stress intensity factor K_I is obtained, and the fracture toughness K_{IC} and the lower limit of stress corrosion K_0 are determined respectively. The results of test show that the curves of $\lg K_I - \lg v$ and $K_I - \lg v$ can be well linear, and the high discretion of data are caused by mineral composition, particle size and mechanical property of rock itself. In addition, the subcritical crack growth with stress corrosion of the ore is caused by the united function of two mechanisms, one is the tensile stress and the other is the material at the crack tip. Chemical reaction takes place between the materials and the corrosion medium in the environment and makes the chemical bond break. So, the obtained results provide reliable references for predicting the block caving velocity of the ore in Jinchuan Mine under high horizontal stress condition.

Key words: subcritical crack growth; fracture toughness; double torsion specimens; stress corrosion; block caving method

1 Introduction

Because of the effects of diagenetic process and tectonic movement, lots of jointed plane of weakness with different contacted characteristics exist in the practicable rock mass. The deformation and fracture mechanisms of the rock mass are closely related with the cracks generating, extending and coalescing. So, more and more people think much of the long-term stability of rock engineering. And the extending mechanisms correlating with the environment of cracks are becoming a studied focus.

According to the principle of fracture mechanics, before the stress intensity factor K_I reach the value of fracture toughness K_{IC} , the opening crack in certain environment medium has a steady, quasi-static propagation process which is called subcritical crack growth (hereafter referred to as SCG). In this course, the crack growth speed increases with the increase of K_I . The fast extension of the crack and then rupture, usually happens when the subcritical crack propagates to certain extent in the rock[1, 2]. Rock mass fracture mechanics provides the criterion and direction of the special single crack or of the regular distributed crack in the homogeneous material. A lot of domestic and international scholars have made a large number of

experimental researches in the two respects of crack propagation and rock breakage caused by crack propagation[3-9]. These studies have offered us an ocular and effective way to understand the process and the law of crack propagation. However, the studies had been made mainly for the brittle materials such as glass, ceramic, and hard rock. The studies on flabby and intricate rock were few. And the mechanism studies on them were less.

The double torsion (hereafter referred to as DT) load-relaxation method has been widely used as the most reliable method for measuring SCG curves $K_I - v$ owing to the great stability of the four-point bending loading configuration. It needn't monitor the crack length during the test[10]. In this study, the stress-corrosion mechanism of rock SCG and the keystone of DT test are firstly introduced, and then SCG of the flabby and intricate ore rock in Jinchuan Mine is tested. Our studies will be centralized on the propagating mechanism of SCG in weak and intricate rock. The obtained results provide the reliable references for predicting the block caving velocity of ore in Jinchuan Mine under high horizontal stress condition.

2 Experimental keystone of DT specimens

DT specimen was adopted firstly by WILLIAMS

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and EVANS(1973). It can be regarded as a symmetrical system of two independent elastic torsions (see Fig.1). When the width of torsion is far greater than the thickness of specimen, the relation between the strain-energy release rate g of crack propagation and the compliance C of the specimen is[11]

$$g = \frac{F^2}{2} \left(\frac{dC}{dA} \right) \quad (1)$$

where[12]

$$C = y/F = \frac{3W_m^2 a}{Wd^3 G} \quad (2)$$

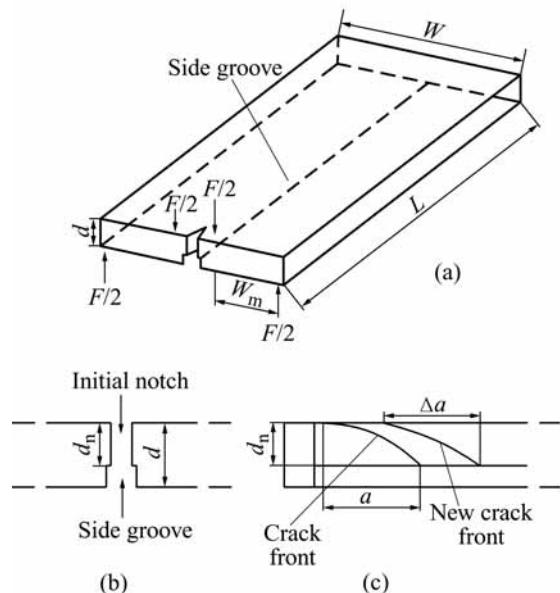


Fig.1 Double torsion specimen

In Eqns.(1) and (2), F is the applied load on torsion, G is the shear modulus, a is crack length, d is the thickness of specimen, W the width of specimen, W_m the moment arm of the torsion and y is constant displacement imposed on the loading point.

Substituting Eqn.(2) into Eqn.(1), we obtain

$$g = \frac{3F^2 W_m^2}{2Wd^3 d_n G} \quad (3)$$

According to the relation between the stress intensity factor K_I and the strain-energy release rate g , and the relation of the Poisson's ratio μ and shear modulus G of the rock, the stress intensity factor can be derived:

$$K_I = \sqrt{Eg} = FW_m \left[\frac{1+\mu}{\eta Wd^3 d_n} \right]^{1/2} \quad (4)$$

where E is the elastic modulus and η is a factor depending on the ratio W/d (EVANS assumed $\eta=1/3$ in 1972).

According to the relation between the compliance of specimen and the length of crack, the relation between the change rate of compliance and subcritical propagation of crack can be set up. Test indicates that the change rate of compliance can be obtained through the change rate of displacement under invariable loads or the change rate of loads under invariable displacement. Under the invariable displacement condition, the subcritical crack velocity of rock equals[12]:

$$v = \frac{da}{dt} = - \frac{Wd^3 E y}{6W_m^2 F^2 (1+\mu)} \frac{dF}{dt} \quad (5)$$

Eqn.(5) shows: if the size of specimen and the displacement on loaded point are known, subcritical crack velocity relates to the load relaxation rate in current loads under the displacement state has been given. Therefore, we can establish the relation between stress intensity factor K_I and subcritical crack velocity v through the test.

Aiming at the stress corrosion mechanism of SCG in glass and ceramic, researchers have brought forward some theories primarily such as CHARLES theory (1959) and HILLING and CHARLES theory (1964)[3, 13].

1) CHARLES theory assumes that the tensile stress made the space of atoms in glass larger, and then the alkaline ion was easier to diffuse, which caused stress corrosion. Because the stress is centralized, and tensile stress is very great in the crack tip, the diffusivity of alkaline ion is more serious. When the temperature is constant, CHARLES equation can be shown as linear function of double logarithmic space $\lg K_I - \lg v$ or power function of space $K_I - v$:

$$\lg v = a_1 + b_1 \cdot \lg K_I \quad (6)$$

or

$$v = A \cdot K_I^n \quad (7)$$

where $b_1=n$, sometimes it is called stress corrosion factor.

2) HILLIG and CHARLES theory assumes that the stress corrosion was caused by the chemical reaction happened between materials forming the crack tip and materials in the environment, where water in the crack offer the abundant reactant. Therefore, HILLIG and CHARLES equation can be denoted as linear function of half logarithmic space $K_I - \lg v$:

$$\lg v = a_2 + b_2 \cdot K_I \quad (8)$$

In Eqns.(6), (7) and (8), A , a_1 , b_1 , a_2 and b_2 are all constants.

3 Experiment of SCG

The ore rock specimens fetched from the drill cores

in Jinchuan Mine, were cut, rubbed to plates and processed into six DT specimens subtly, whose dimensions are 150 mm in length, 48 mm in width and 4.8 mm in thickness. The leading groove in the middle of specimen was cut by a saw with diamond. The grooves were 2 mm in width and 1/3 thickness in depth. Errors of Parallel degree on the surface of specimen were less than 0.025 mm. In order to make the crack easy to propagate along the central groove, each of the present specimens was created V initial notch, deep about 1 mm in the position of the load direction near grooves. After prepared well, the specimens are split in advance at the invariable moved speed 0.05 mm/min on the material servo testing machine of INSTRON 1342 in the testing center of Central South University.

The test of SCG adopts the constant-displacement load-relaxation-configuration method and loads on the servo examinational machine. The specimen was loaded fast at the speed of displacement v_i 0.5–5.0 mm/min at the initial stage of test. The relaxing test begins when the loading reaches a specific load value near the peak value F_1 . Keep the parameter of displacement y invariable until the change of load is not obvious. In the whole process, the relaxing time is t and the loading steady value is F_2 . At last, Fig.2 and Fig.3 show the curve F — t of load's change over time and y — t of displacement's change over time of JC1 specimen respectively. All of the above mentioned parameters are shown in Table 1.

In relaxing process of the test, the specimens JC1 to JC4 and JC6 were successful, where the cracks propa-

Table 1 Testing data of load and displacement

No.	v_i (mm·min ⁻¹)	t /min	F_1 /N	F_2 /N	y /mm
JC1	0.54	18.437 2	201.944	177.999	0.164 01
JC2	2.10	15.624 1	202.320	178.078	0.174 59
JC3	2.09	19.983 3	179.820	160.378	0.174 26
JC4	2.20	25.316 7	184.820	167.869	0.183 36
JC6	1.32	23.952 9	160.001	148.729	0.149 15

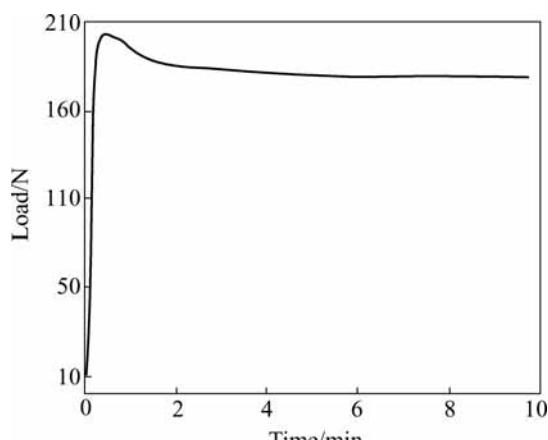


Fig.2 Loading curve of JC1 specimen

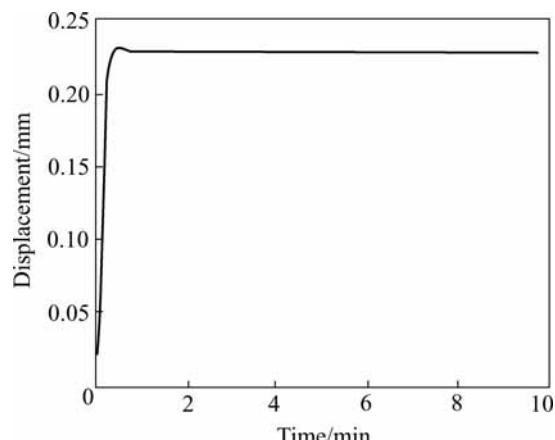


Fig.3 Displacement curve of JC1 specimen

propagated along the leading grooves. Because of some reasons just like loading and the little cracks lied in the specimen JC5, the crack did not propagate along the leading groove during the loading process, and the test failed.

After the relaxation test, the specimens were loaded fast at the speed of displacement of 20 mm/min until destroyed. Finally, the steady load F_m was obtained. Then, the value of fracture toughness K_{IC} of the weak complicated ore in Jinchuan Mine was calculated by utilizing Eqn.(4).

4 Analysis of results of test

Stress corrosion of rock is a very complicated course. In order to checkout comparatively the results of the test more accordant to CHARLES theory or HILLIG and CHARLES theory, the data related to ore rock of Jinchuan Mine were calculated by a least-squares linear regression with Eqns.(6), (7) and (8). All of the regressions were done in the double logarithmic space ($\lg K_I - \lg v$) and the half logarithmic space ($K_I - \lg v$), and the results of regression are listed in Table 2, where r is a multiple correlation coefficient.

To the same set of relaxing data, it can be seen from Table 2 that the multiple correlation coefficient r regressed by Charles equation is slightly higher than by HILLIG and CHARLES equation, but the average value are all more than 0.924. According to the quantity of the discrete data each test, we can find the significance level $\alpha=0.01$ through looking for the test table of multiple correlation coefficient of linear regression. The significance level is so high that the two kinds of theories can both well explain the results of the test. So we can consider that SCG with stress corrosion of the ore is caused by the united function of two mechanisms, one is the tensile stress of the ore, the other is the materials at crack tip. Chemical reaction takes place between the material and corrosion medium in the environment and it

Table 2 Recursive coefficient of testing results

No.	a_1	A	b_1 or n	γ_1	a_2	b_2	γ_2
JC1	-11.170 4	6.7546×10^{-12}	59.812 7	0.914 7	-30.773 5	20.316 1	0.913 6
JC2	-8.653 5	2.2208×10^{-9}	61.211 8	0.920 8	-31.110 8	22.753 8	0.919 5
JC3	-9.809 3	1.5513×10^{-10}	56.880 0	0.932 8	-29.903 0	20.475 2	0.931 5
JC4	-10.453 2	3.5221×10^{-11}	54.939 0	0.921 2	-28.565 3	18.743 2	0.920 9
JC6	-12.442 8	3.6074×10^{-13}	66.824 3	0.937 5	-34.003 2	22.436 3	0.938 1
Average	-10.505 8	3.1200×10^{-11}	59.933 6	0.925 4	-30.871 2	20.944 9	0.924 7
	$\pm 1.273 8$	$\pm 9.8092 \times 10^{-10}$	$\pm 4.084 1$	$\pm 0.008 4$	$\pm 1.796 2$	$\pm 1.480 5$	$\pm 0.008 8$

makes the chemical bond break.

On the $F-t$ curve, some data point of time, corresponding values of load and displacement were chosen from the load peak value beginning and input into the computer program, including the size of specimens, the position of loading point and the rock mechanics parameters of specimens together. Finally, the loading relaxation rate dF/dt was calculated, and the relation of K_I at crack tip and v of the corresponding data point were obtained, using Eqn.(4) and Eqn.(5). Fig.4 and Fig.5 show the logarithmic space relations of K_I and v of the weak complicated ore rock in Jinchuan Mine.

It can be found from Fig. 4 and Fig. 5 that the

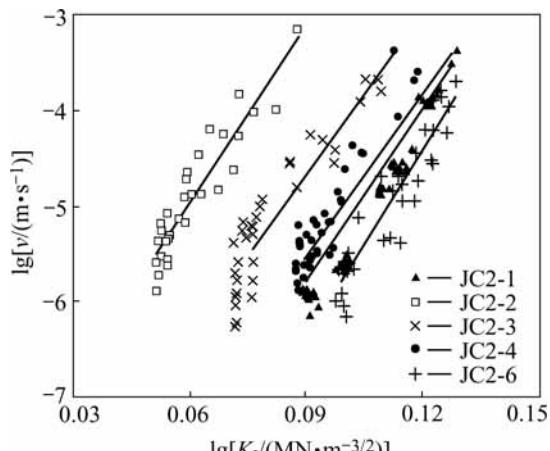


Fig.4 Double logarithmic space lgK_I — lgv

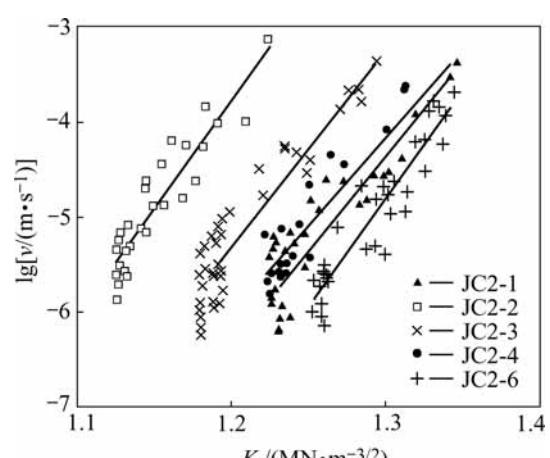


Fig.5 Half logarithmic space K_I — lgv

curves of lgK_I — lgv and K_I — lgv can be well linear, but the data measured in the relaxation test keep high discretion. After researching carefully, it is thought that the high discretion of data are caused by mineral composition, particle size and mechanical property of the rock itself. In order to reduce the dispersed influence to results, the tests of the same kind of rock should be done many times using the constant-displacement load-relaxation method, and the average values of the regressed coefficients must be taken as the characteristic parameters of the subcritical crack of the rock.

During the test, the speed of little crack propagation of the ore rock can be detected intervening between 1.0×10^{-7} m/s and 1.0×10^{-8} m/s. The crack propagation is close to stagnancy at this moment. Speaking from the engineering meaning, the speed at 1.0×10^{-7} m/s can be thought the crack has already stopped to propagate. Therefore, the speed at 1.0×10^{-7} m/s is looked as the speed of stagnancy. When the speed of the crack growth is less than 1.0×10^{-7} m/s, the corresponding stress intensity factor K_I is regarded as the lower limit of stress corrosion K_0 . According to this assumption, the ratio K_0/K_{IC} of the flabby and intricate ore in Jinchuan III Mine can be calculated under the dry condition (see Table 3).

Table 3 K_0/K_{IC} value of ore under dry condition

No.	$K_0/(MN \cdot m^{-3/2})$	$K_{IC}/(MN \cdot m^{-3/2})$	K_0/K_{IC}
JC1	1.231 8	1.734 2	0.710 3
JC2	1.126 3	1.441 2	0.781 5
JC3	1.179 8	1.477 1	0.798 7
JC4	1.224 4	1.425 6	0.858 9
JC6	1.253 8	1.463 7	0.856 6
Average	1.2032 ± 0.0454	1.5084 ± 0.1143	0.8012 ± 0.0549

5 Application of testing results

The ore body of lean ore is slantwise (60° — 70°), thick and big, cracked, relatively low in its intensity and overgrown in its joint crack at III mining area of Jinchuan Group Ltd. Because of these particularities of the ore rock itself, the usual backfill mining method cannot be used at present. In 2002, proved synthetically

by several scientific research institutions and studied carefully by the company, block caving method with low costs and high efficiency is adopted[14, 15]. This test has measured the relation of K_I — v and the fracture toughness K_{IC} of ore rock at stope. According to the stress state and the joint distribution of the stope, the contour surface of the dangerous stress intensity factor can be found. The position and shape of the surface can be influenced by the position and process of the undercutting project, and be made more apropos by adjusting the undercutting work. And then according to the K_I — v relation of ore, the block-caving time of the ore under the dangerous surface can be calculated, where time is also named as one caving necessary time and the ore is one caving ore-quantity. So the speed of block caving can be calculated finally.

To the flabby and intricate ore of Jinchuan Mine, the testing results indicate that the block caving is a course, where the joints and cracks in the ore body propagate subcritically and reach the critical length of crack mainly under the tensile stress condition, which causes the cracks to propagate fast and finally engender breakage and caving under the gravity of the ore mass itself.

So, the test is not only significant in theory, but also has direct realistic meanings in actual production. The results of the test have provided reliable references for predicting the block caving velocity of the ore in Jinchuan Mine.

6 Conclusions

1) The DT method is intuitionistic, strong in adaptability and simple in the loading mode to test SCG and the fracture toughness of the rock, and the shape of specimen is simple and needn't demarcate the compliance. The analyzing and researching have shown that the method is effective, and the testing results are reliable.

2) The relational curves of lgK_I — lgv and K_I — lgv can be well linear, and the high discretion of data are caused by mineral composition, particle size and mechanical property of the rock itself. In order to reduce the dispersed influence to results, the tests of the same kind of rock should be done many times using the constant-displacement relaxation method, and the average values of regressed coefficients must be taken as the characteristic parameters of the subcritical crack of the rock.

3) The SCG with stress corrosion of ore in Jinchuan Mine are caused by the unite function of two mechanisms, one is the tensile stress of ore, the other is the materials at crack tip having chemical reaction with the corrosion medium in environment and making

chemical bond break.

4) According to the testing results, the average value of the fracture toughness K_{IC} of the ore rock in Jinchuan III Mine is $1.5084 \pm 0.1143 \text{ MN/m}^{3/2}$, and speaking from the project meaning, the average value of the lower limit of stress corrosion K_0 is $1.2032 \pm 0.0454 \text{ MN/m}^{3/2}$.

5) About the measure of testing the fracture of rock and the study of SCG, some beneficial explorations were done in the test. The test is not only significant in theory, but also has direct realistic meanings in actual production. The obtained results have provided reliable references for predicting the block caving velocity of ore in Jinchuan III Mine.

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