Acoustic Emission During Slow Crack Growth

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Abstract

Double torsion testing was carried out to clarify the relationship between the crack growth rate and mode I stress intensity factor at the crack-tip and to investigate the characteristics of acoustic emissions associated with subcritical crack growth. Rocks used were Murata basalt and Oshima granite. Dominant frequency of acoustic emissions ranged from 100 kHz to 1 MHz, which obviously corresponds with the frequency range of acoustic emissions under usual uniaxial compressive loadings. Acoustic emission rate showed the close relation with the growth rate of the crack. A tendency that the dominant frequency decreased with the increase in crack velocity was observed.

Introduction

Fracture development within rock is known to be rate-dependent. Dilatancy under constant load is one of the most representative phenomena called brittle creep. Furthermore, dilatancy under constant strain rate and the strength of rock are dependent on strain rate. Scholz[1)], Cruden[2)], Mizutani *et al.*[3)] and Sano[4)] suggested that the subcritical crack growth due to stress corrosion plays a major role in the time-dependent behaviour and also in the environment-sensitive characteristics of rocks.

Stress corrosion has been shown to occur in metals, glasses and ceramics. The subcritical crack growth was observed also on such rocks and rock forming minerals as the single crystal of quartz[5)], marble[6)], novaculite[7)], andesite and basalt[8)]. Double torsion testing developed by Evans[9)] is appropriate for such opaque materials as rocks to determine the relation between the growth rate of the crack, $\dot{c}$, and mode I stress intensity factor, K_I, at the crack-tip, for K_I is independent of the crack length.

Acoustic emissions have been observed on rocks under various loading conditions and are attributed to microfractures, that is, the fast-moving cracks within rocks[10),11)]. Monitoring of acoustic emissions is a useful tool to investigate the mechanisms of the fracture development within rocks in laboratory, and has a possibility of the location of the highly stressed region and the prediction of such hazards as rock-bursts in situ.

During slow crack growth, acoustic emissions have been detected. The acoustic emission rates showed the close relation with the growth rates of the crack for porcelain[12)] and gabbro[13)]. Byerlee and Peselnick[14)], however, reported that the slow crack extension without acoustic activities was observed on glass plates with a slit under compression.

In this paper, we shall deal with the frequency characteristics of the acoustic

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emissions during slow crack growth and the relation between the crack velocity and the acoustic emission rate.

Experimental procedure

Crack growth rate and the stress intensity factor at the crack-tip were determined by double torsion technique developed by Evans[9]. A schematic expression of the measurement system and the specimen's configuration are shown in Fig. 1 and Fig. 2, respectively. Rocks studied are Murata basalt and Oshima granite whose physical properties are listed in Table 1. The specimens were cut parallel to each other by a diamond saw and then ground flat and parallel by a lathe. Each specimen was 4 cm wide × 3 mm thick × 10 cm long. Guide groove was precut to 1 mm in width and 0.5 mm in depth.

Each measurement was carried out under constant load which was raised incrementally. Mode I stress intensity factor at the crack-tip was calculated according to Williams and Evans[15], namely

$$K_I = PW_m\left(\frac{3(1+\nu)}{Wd_n d^3}\right)^{\frac{1}{2}}, \tag{1}$$

where P is a total load, W is the width of the specimen, W_m is the moment arm, d is the

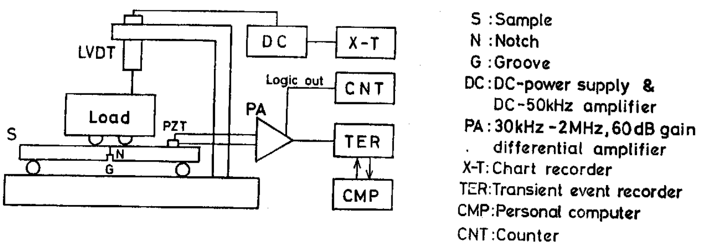

Fig. 1 A schematic representation of the measurement system. Load was applied by a dead load.

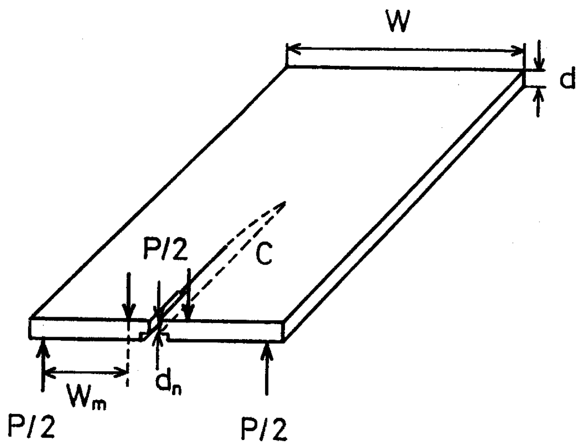

Fig. 2 A schematic expression of the specimen's configuration. The same notations as equations (1) and (2) are used.

Table 1. Physical properties of Murata basalt and Oshima granite.

Rock type	Young's modulus, GPa	Poisson's ratio
Murata basalt	72.4	0.24
Oshima granite	60.9	0.28

specimen's thickness, d_n is the plate thickness at the crack plane and v is Poisson's ratio. The deflection, y, of the plate is also given by Williams and Evans, namely

$$y = \frac{6W_m^2 P(1+v)c}{Wd^3E} \tag{2}$$

where c is the crack length and E is Young's modulus. The rate of the crack-growth was estimated by the deflection rate which was measured by a linear variable differential transformer (LVDT).

Acoustic emissions were detected by plumbum-titanate-plumbum-zirconate (PZT–7) disks which are resonant at 1 MHz. Amplification was achieved by a differential pre-amplifier which has a 60 dB gain, input impedance of 1 MΩ and output one of 50 Ω. The pre-amplifier has a voltage comparator with a variable voltage reference. This comparator in combine with a time-delay unit enabled us to count the events of acoustic emissions. The over-all frequency response of the amplifier is 30 kHz to 2 MHz.

The signals of the acoustic events randomly sampled were stored digitally by a transient event recorder which has a memory length of 1024 words and a digitized interval varying from 50 ns to 1 s. Fourier analyses were carried out by a mini-computer which was connected with the transient event recorder by the IEEE–488 interface bus.

In order to avoid temperature effects, all experiments were performed in a thermostatic chamber. Room temperature was held constant within ±0.1 K in the comparatively short period (every 2 or 10 minutes), ±0.2 K in 1 or 2 weeks, and ±2 K in a year.

The uncertainty in the estimation of the stress intensity factor is about ±3% due to the fluctuation of the parameters in equation (1). In the crack velocity measurement, fluctuation would exist within ±20%. Acoustic emission rate will fluctuate within ±20% due to the difference in the sensitivity of the sensor when the different sensor was used.

Results and Discussion

The results of the crack growth measurements are shown in Fig. 3. Data are plotted on double logarithmic co-ordinates. Experimental results indicate the power-law dependence of the growth rate of the crack on the stress intensity factor, K_I. The relation between the crack velocity, $\dot{c}$, and mode I stress intensity factor at the crack-tip is generally expressed by[16]

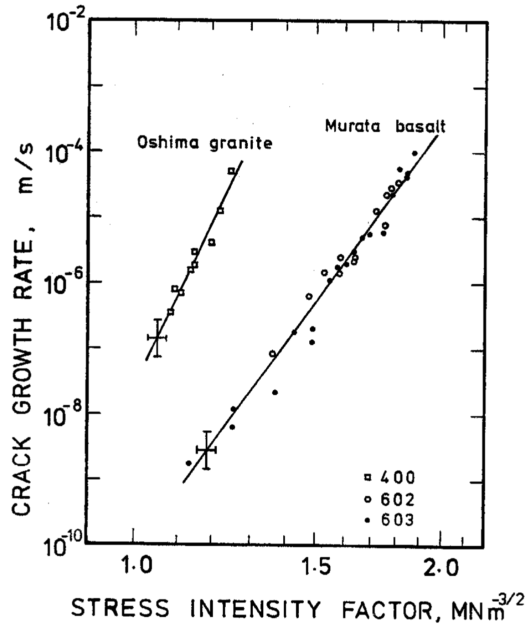

Fig. 3 Relation between the crack velocity and mode I stress intensity factor at the crack-tip. Data are plotted on double logarithmic co-ordinates. The same results can be fitted to straight lines also on log-normal plots.

$$\dot{c}=AK_I^n \tag{3}$$

or

$$\dot{c}=\dot{c}_0 \exp\{(-E^*+bK_I)/kT\} \tag{4}$$

where A, n, $\dot{c}_0$, E^*, and b are experimentally determined constants, T is temperature and k is Boltzman's constant. The varying range of the crack velocity is so large compared with the stress intensity factor that these data also agree well with the equation (4).

The least squares fit of a straight line to data shows the exponent in equation (3) to be 30 ± 5 and 22 ± 2 for Oshima granite and Murata basalt, respectively. The result for Oshima granite is in harmony with the prediction of Sano[4)] who suggested that the exponent, n, should be 32 ± 2 for Oshima granite and around 30 for silica rich crystalline rocks according to the observed effects of the strain rate on the uniaxial compressive strength of rocks. The stress corrosion index of Murata basalt is quite similar to the one obtained by Atkinson[7)] for novaculite.

Figures 4 and 5 show the relation between the acoustic emission rate, dN/dt, and the crack growth rate. Straight lines in the figures indicate the following relationships, namely

$$\dot{c}\propto\frac{dN}{dt} \tag{5}$$

or

$$\frac{dN}{dt}=A_1K_I^n \tag{6}$$

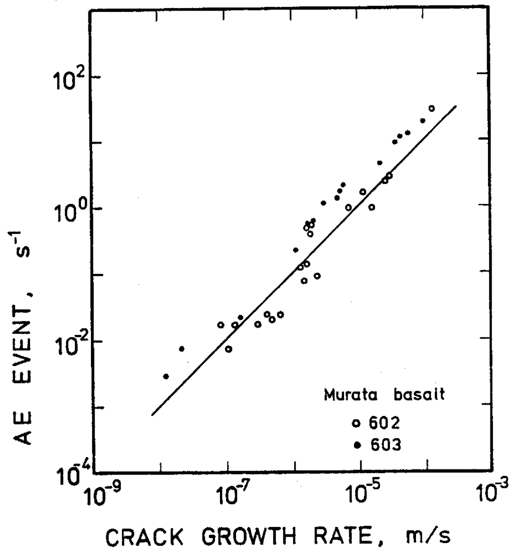

Fig. 4 Relation between the acoustic emission rate and the crack velocity observed on Murata basalt. Straight line indicates a proportionality of the count rate to the crack growth rate.

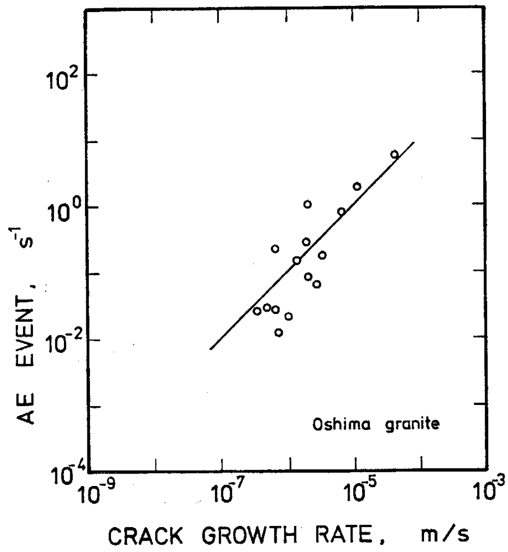

Fig. 5 Relation between the acoustic emission rate and the crack velocity observed on Oshima granite. Straight line indicates a proportionality of the count rate to the crack extension rate.

where A_1 is experimentally determined constant. For Murata basalt, these data can be fitted to these straight lines and the acoustic emission rate can be expressed by the equation (6). The result for the specimen No. 602 slightly shifts upward of the one for the specimen No. 603. This can be attributed to the difference in the sensitivity of the sensor-rock systems and does not affect the expression as equation (6).

For Oshima granite, the result exhibits considerable scatter due to probably the heterogeneity of this rock. The same tendency as Murata basalt, however, can be seen qualitatively. The exponent, n, seems slightly larger than the one determined by the relation between the crack growth rate and the stress intensity factor. Evans and Linzer[12] showed the same relation as Murata basalt for porcelain. Atkinson and Rawlings[13] showed that the ring down count rate of the acoustic emissions, $\mathrm{d}N_R/\mathrm{d}t$, obeys the following expression, namely

$$\frac{\mathrm{d}N_R}{\mathrm{d}t}=A_2K_I^{n_R}$$

where A_2 is the experimentally determined constant and n_R is similar to n. Atkinson and Rawling's result is in harmony with the ones for Murata basalt and Oshima granite. Their result that the exponent, n_R, is slightly larger than n is in accord with the one for Oshima granite qualitatively.

Typical power spectrum of the acoustic emission during slow crack growth is depicted in Fig. 6. Dominant frequency ranges from 100 kHz to 1 MHz, which obviously corresponds with the frequency range of the acoustic emissions under usual uniaxial compressive loadings[11]. Figure 7 shows the relation between the frequency

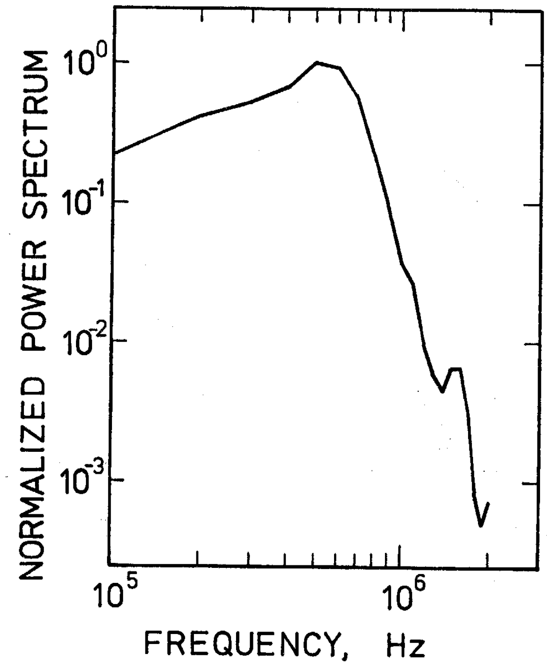

Fig. 6 Typical power spectrum of acoustic emission during slow crack growth. This datum was observed on Murata basalt. Dominant frequency ranges from 100 kHz to 1 MHz.

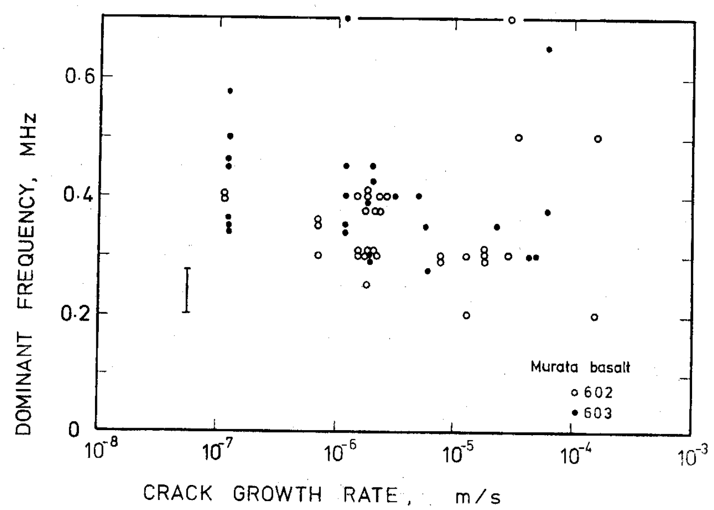

Fig. 7 Frequency at the maximum power spectrum vs crack velocity. A clear tendency that the dominant frequency decreases with the increase in the velocity can be observed.

at the maximum power spectrum and the crack velocity observed on Murata basalt. There can be seen a clear tendency that the dominant frequency gradually decreases with the increase in the rate of the crack extension. The change in the dominant frequency is not due to the change in the physical properties of the propagating path but the alteration of the source parameters of the microfractures, for acoustic emissions occur almost in the centre plane including the crack[17] and does not occur in the region of the wave propagation.

According to the results of source location of the acoustic emissions[17),18)], micro-fractures occur not only at the crack-tip but also beyond and behind the apex of the crack. The sources of acoustic emissions are, therefore, at least two causes. One is the frictional cause probably at the contact of the already cracked planes. The other is the microfractures associated with the pre-existing microcracks. There are many pre-existing cracks within the rock plate. When load is applied, the stress concentration near the crack-tip of these pre-existing microcracks will rise and these cracks will grow due to stress corrosion. Heterogeneity of rock is also the cause of the stress concentration. When cracks extend to some critical length, rapid extension of these cracks will occur and acoustic emissions will be observed. As the highly stressed region is restricted to the neighborhood of the macroscopic crack, these occurrences of the microfractures should be influenced by the extension of the macroscopic crack.

The microfractures occurring ahead of the macroscopic crack should affect the deflection of the plate.

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