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Critical Crack Speed and Fractoemission in Brittle Materials

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Fracture of materials gives rise to the emission of atoms, electrons and photons called fractoemission. In this study, fracture-induced atom emission in brittle materials such as glass and ceramics is studied by means of computer simulations. The simulations have been performed using a two-dimensional model system of particles connected by elastic springs. Tensile fracture of the system has been followed for different crack speeds. The simulations show that the number of emitted particles increases drastically when the crack speed exceeds a critical speed. The existence of the critical crack speed is also manifested by the elastic energy released from the system. Above the critical crack speed, the aspect of fracture changes from crack propagation to particle emission. This also causes the roughness of fracture surfaces and the saturation of temperature near fracture surfaces. The critical crack speed for fractoemission should be one of important properties characterizing dynamic fracture in brittle materials.

Key words: fracture, crack, fractoemission, simulation, brittle materials

1. INTRODUCTION

When solid materials are fractured, particles such as atoms, molecules, ions, electrons and photons are emitted from fracture surfaces. This particle emission is called fractoemission. Fractoemission has been observed in a variety of materials such as glass, polymers and metals. Although fractoemission is of importance in understanding fracture dynamics, its mechanism is not yet clear up to date.

In this paper, fractoemission is studied by means of computer simulations using a two-dimensional model system. In particular, the relation between crack speed and fractoemission is investigated. We will show that there is a critical crack speed above which intense fractoemission appears. In other words, above the critical crack speed, the aspect of fracture changes from crack propagation to particle emission.

2. EXPERIMENTAL REPORTS

There have been several experimental studies on fractoemission reported in the literature. Dickinson *et al.*[1-6] reported many measurements of fractoemission for various materials. They reported a variety of characteristics of fractoemission such as the time dependence of emission intensity, the energy distribution of emitted particles and the relation between emission and load at fracture. In particular, they observed that the emission continues for such a long time as several minutes and that there are emitted particles with energy of several hundreds of eV.

Gonzalez and Pantano[7] measured fractoemission from silica glass in vacuum. They reported that no fractoemission is observed in fracture with slow crack speed up to 10^{-3} m/s but fractoemission is observed only in fracture with fast crack speed. They suggested that intense fractoemission is due to dissipation of the excess energy associated with unstable crack growth.

Boudet *et al.*[8] studied experimentally the instability of crack propagation in plexiglass. They observed intense sound emission when the crack speed exceeds a critical value of about 500 m/s. They also observed that fracture surfaces roughen above the critical crack speed.

Observations reported to date show that there may be a certain critical crack speed above which the instability of crack propagation, the intense acoustic emission and the roughness of fracture surfaces appear rapidly. Fractoemission is considered as a phenomenon associated with these observations. An investigation of fractoemission will be necessary in connection with crack speed and the instability of crack propagation.

3. MODEL SIMULATION

We use a simple model system in order to study the relation between crack speed and fractoemission. As shown in Fig.1, we set particles on the two-dimensional triangular lattice. Each particle is connected to nearest-neighbor particles by elastic springs. We assume that each spring is broken if its length exceeds a certain value.

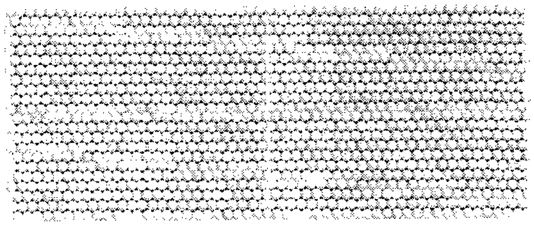

Fig. 1 Model system for simulation of fractoemission: particles are located on the two-dimensional triangular lattice and are connected to nearest-neighbors by elastic springs.

We perform simulations of tensile fracture of the system as follows. The system is pulled in the upward and downward direction with tensile strain ε and particles are optimized so as to minimize the total elastic energy of the system. Then several springs are broken in the left side end of the system, that is, an initial crack is introduced. If the tensile strain is large enough to break springs near the initial crack tip, the crack can propagate. We follow the movement of particles after the initial crack is introduced.

We define emitted particles as isolated particles. In other words, all springs around an emitted particle or a group of emitted particles are broken. We investigate the relation between the number of emitted particles and the crack speed. The crack speed can be estimated by the time dependence of the number of broken springs and can be varied by changing the value of tensile strain of the system.

We set the particle mass as $m = 1$, the spring constant as $k = 1$, and the nearest-neighbor distance of particles as $a = 2$. A spring has been broken when its length exceeds 1.2 times of its natural length. The up and down boundaries of the system in Fig.1 are the fixed end and the left and right boundaries are the free end.

4. SIMULATION RESULTS

We here show the results of the system composed of 1000 (20 × 50) particles. We have checked the size effect on simulation results by also using the system of 4000 (40 × 100) particles. The results are almost the same for both the systems. We have also checked the effect of elastic waves reflected at the boundaries of the system on simulation results by using the systems of 2000 (20 × 50 and 40 × 50) particles. The results are also the same for all systems.

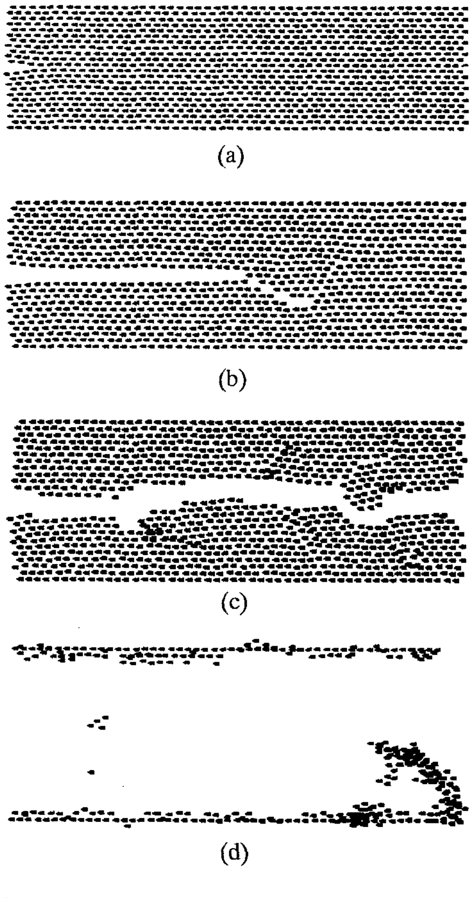

Fig. 2 Snapshots of the systems with different tensile strains: (a) $\varepsilon = 0.08$, (b) $\varepsilon = 0.09$, (c) $\varepsilon = 0.14$ and (d) $\varepsilon = 0.24$.

Fig. 3 Snapshot of emitted particles for the system of $\varepsilon = 0.24$.

Figure 2 shows snapshots of the systems with different strains. The system with $\varepsilon = 0.08$ in Fig.2 (a) shows no crack propagation. The initial crack propagates for the system with $\varepsilon = 0.09$, as shown in Fig.2 (b). When $\varepsilon = 0.14$, the system has been divided into two parts due to crack propagation, but there appears no particle emission, as shown in Fig.2 (c). However most of particles have been emitted after fracture for the system with $\varepsilon = 0.24$, as shown in Fig.2 (d). A snapshot of emitted particles in this case is shown in Fig.3.

Figure 4 shows the dependence of the number of broken springs N_b on the tensile strain ε. Because the crack propagates for the system with $\varepsilon = 0.09$, the

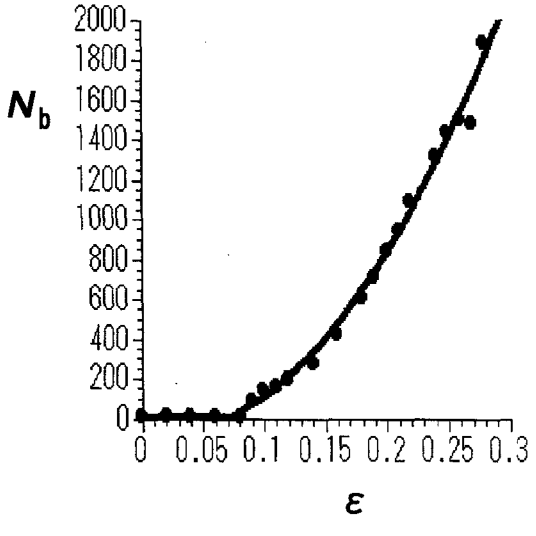

Fig. 4 Dependence of the number of broken springs N_b on the tensile strain ε.

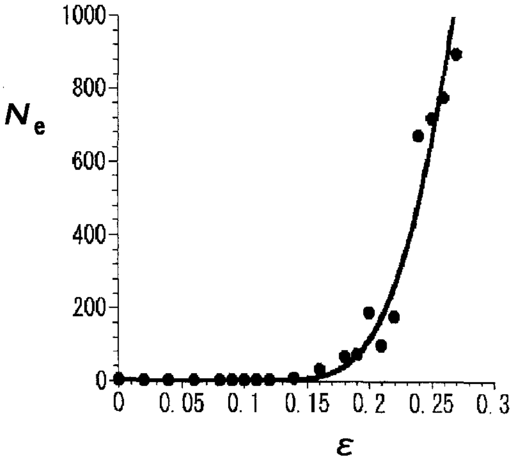

Fig. 5 Dependence of the number of emitted particles N_e on the tensile strain ε .

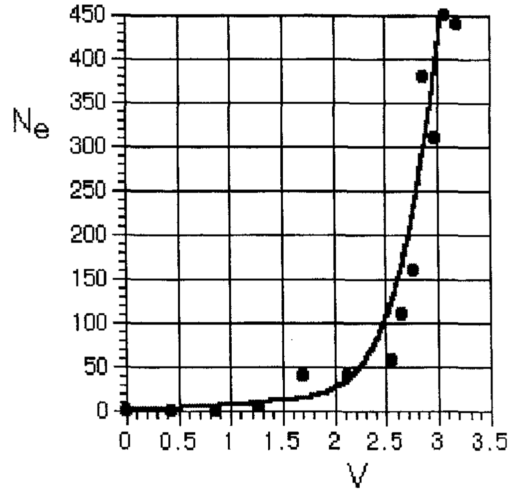

Fig. 6 Dependence of the number of emitted particles N_e on the crack speed V.

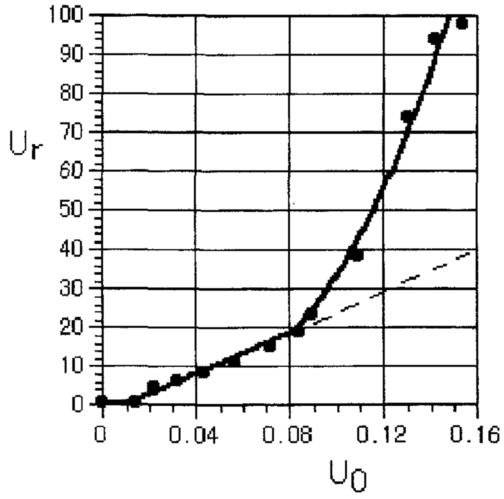

Fig. 7 Relation between the release energy U_r. and the initial elastic energy per particle U_0 .

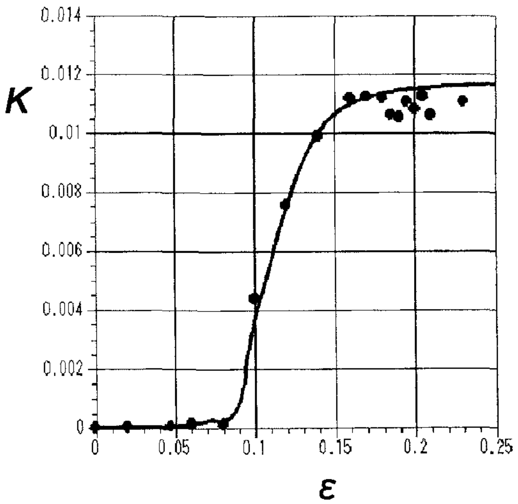

Fig. 8 Relation between the tensile strain ε and the kinetic energy per particle K of the system after fracture.

number of broken springs increases with increasing ε for the systems with $\varepsilon > 0.09$.

Figure 5 shows the dependence of the number of emitted particles N_e on the tensile strain ε . While the number of broken springs increases at $\varepsilon > 0.09$, the number of emitted particles increases rapidly at $\varepsilon > 0.20$. This means that fracture for $0.09 < \varepsilon < 0.20$ is caused only by crack propagation but fracture for $\varepsilon > 0.20$ is accompanied with particle emission. Because the system with larger ε has a faster crack speed, this suggests that there is a critical crack speed above which fracture is accompanied with intense particle emission.

Using the relation between the tensile strain ε and the crack speed, we can plot the relationship between the number of emitted particles N_e and the crack speed V. Figure 6 shows the dependence of N_e on V. The number of emitted particles increases rapidly above $V = 2.2$. Thus we consider the critical crack speed V_c as $V_c = 2.2$ from Fig.6.

The existence of a critical crack speed is manifested by investigating the release energy. Here the release energy is defined as the energy that is released from the system by fracture. Figure 7 shows the relation between the release energy U_r and the initial elastic energy per particle U_0. The release energy increases almost proportionally to the initial elastic energy for $U_0 < 0.08$ in which the energy release process is due to crack propagation, that is, due to breaking springs. However the relation between U_0 and U_r suddenly changes from the linear relation at $U_0 = 0.08$. The release energy increases rapidly with increasing the initial elastic energy because of intense particle emission. The energy release process is almost due to particle emission. The crack speed for the system of $U_0 = 0.08$ is $V = 2.2$ which is identical with the critical crack speed V_c = 2.2 estimated from Fig.6. Thus the sudden change of the increasing rate of U_r supports the existence of a critical crack speed.

5. DISCUSSION

The present simulations have shown the existence of a critical crack speed for particle emission in fracture, that is, for fractoemission. We here estimate the value of the critical crack speed by comparing the present model system with SiO_2. By using the averaged mass, the averaged interatomic distance and the Debye temperature of SiO_2, we can estimate the value of the critical crack speed that corresponds to SiO_2. The estimated value of a critical crack speed is $V_c \sim 800$ m/s. This value is near to $V \sim 500$ m/s above which intense sound wave emission and rough fracture surface were observed for glass[8].

The existence of a critical crack speed suggests the saturation of temperature near fracture surfaces. Figure 8 shows the relation between the tensile strain ε and the kinetic energy per particle of the fractured system K. The kinetic energy per particle is zero for $\varepsilon < 0.09$ because the initial crack does not propagate, but it increases rapidly for $\varepsilon > 0.09$ because crack propagation changes a part of the initial elastic energy into kinetic energy of particles. However the increase of the kinetic energy stops around $\varepsilon = 0.2$ because particle emission occurs and emitted particles take away energy from the system. This implies that temperature near fracture surfaces will saturate. Since thermal equilibrium is not achieved for the present harmonic model system, we can not estimate temperature of the fractured system. Therefore the saturation of temperature is just a suggestion at the present stage.

We have used a rather simple model system, that is, the two-dimensional triangular lattice system for simulations of fractoemission. Since real solid materials, of course, have three-dimensional complicated structure, we have to perform simulations using a more realistic three-dimensional system for detailed discussion. However we believe that fundamental properties in fracture, such as the existence of a critical crack speed for fractoemission, will be manifested even in a simple model system. We expect that fractoemission receives growing attention in order to understand fracture dynamics.

6. CONCLUSION

Simulations based on a simple two-dimensional model system have shown that there is a critical crack speed above which intense farctoemission appears. Fracture is due to crack propagation if crack speed is slower than the critical speed, but it is accompanied with intense farctoemission if crack speed is faster than the critical speed. Thus the aspect of fracture changes drastically from crack propagation to particle emission at the critical crack speed. This change is also associated with intense acoustic emission and roughness of fracture surfaces. The critical crack speed for fractoemission should be one of important properties in fracture dynamics.

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