Impact damage patterns studied by a model simulation

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A lattice model has been developed to explore impact damage patterns in brittle materials. The damage evolution was modelled as a process involving the change of strain-energy distribution by cracking. Using a cubic lattice system, a large strain energy was supplied to the system surface. Crack growth initiated by this local energy supply was followed by means of computer simulations. The damage patterns were compared for systems which have different distributions of strain energy stored prior to the local energy supply. The simulations reveal a characteristic difference in the damage pattern. Impact damage for a system with a spatially fluctuating distribution of strain energy is limited around an impact point. Impact damage for a systen with a relatively uniform distribution of strain energy penetrates deeply. The results of the simulations are discussed in connection with the material evaluation and the material resistance.

1. Introduction

Impact fracture of materials is one of the most important subjects in fracture studies. The resistance to an impact shock has been an essential factor in characterizing structural materials such as body materials of vehicles. Impact fracture is also an important subject for recent advanced functional materials as well as structural materials, because they are often exposed to severe environments such as particle bombardments. Therefore, the investigation of impact fracture phenomena has received increasing attention in connection with the reliability of materials. There have been a number of studies of this subject reported in the literature [1].

Because impact fracture is a very complicated process, there have been many investigations from different points of view. From the experimental side, some authors investigated propagating shock waves which cause impact fracture [1]. Other authors measured the microscopic structure of the surface damaged by an impact shock [1]. From the theoretical or computational side, there have been conventional analyses based on the continuum elasticity theory and fracture mechanics [2]. In recent years several studies based on molecular dynamics simulations have been reported [1, 3]. However, there has been little information about the impact damage pattern.

The investigation of crack patterns has received considerable attention in recent years. One of the stimuli of the investigation was the evaluation of fracture surfaces in terms of fractals [4]. The consideration of crack patterns in terms of fractality has thrown new light on the evaluation of complicated cracks [5]. Another stimulus was the development of computer simulations based on simple models from a fundamental point of view [6–16]. One of the simulations showing an interesting crack pattern has been reported by Meakin and co-workers [13, 14], who performed computer simulations using a two-dimensional spring network model. Crack patterns revealed by their simulations were in good agreement with experiments by Skjeltorp and Meakin [15], who observed the development of a crack pattern using a monolayer of microspheres. Crack patterns caused by quenching have been simulated by Mori *et al.* [16], who have discussed a change in the pattern using a two-dimensional lattice model.

Although many investigations on crack patterns have been reported recently, the global evaluation of impact damage has not been explored extensively. The main motivation of the present study was some questions about impact damage from a global point of view. For example, what can we say about material characteristics from the damage pattern? How can we predict the nature of material fracture before the material is subjected to an impact damage? In this paper we will show that a lattice model based on energetics gives some responses to these questions. In our model, not only the crack pattern on the surface but also the penetration depth of cracks can be followed through computer simulations. We will show that the impact damage pattern is dominated by the distribution of strain energy stored prior to impact damage. The results of the simulations also will be discussed in connection with the material evaluation and the material resistance.

2. Model and simulation

2.1. Modelling

Conventionally, the initiation and propagation of cracks has been described in terms of stress and strain fields based on the continuum elasticity theory and fracture mechanics [2]. Several elaborated methodologies, such as the finite element method and the boundary element method, have been developed to date. A number of studies based on stress–strain analysis have been reported. Although these approaches have been powerful for the evaluation of stress and strain fields around a single or a few cracks, it is not easy to pursue the growth of many cracks in three dimensions at present. In the consideration of the pattern of many cracks, such as impact damage, the global features of many cracks, rather than the details of the cracks, are of significance. In the present study, therefore, we will consider a simple approach to crack growth based on energetics in order to discuss the global features of impact damage.

In previous papers [17, 18], we developed a model for crack growth using a lattice system, in which crack growth was modelled as a process involving the change of strain-energy distribution. The crack patterns revealed by model simulations corresponding to thermal shock-induced fracture [19], were qualitatively consistent with crack features in experimental reports [20, 21]. In the present paper, we extend a previous model to impact fracture.

When the surface of a material is subjected to a local impact shock, the material stores a large strain energy within a local region. This strain energy can be enough to initiate and propagate cracks from the surface to the interior of the material. Then fracture of the material is a process by which the stored strain energy dissipates spatially through crack growth. In terms of strain energy, crack growth can be conceived as follows. A crack initiates when the strain energy stored in a material exceeds a threshold locally. On the initiation of a crack, part of the strain energy is transformed into other energy forms. In other words, it is expended in the forming of a crack plane and emission of acoustic waves. Also the spatial distribution of strain energy in the material is changed by cracking. Strain energy is almost lost near both sides of the crack and is concentrated near the crack tips as a result of stress concentration near the crack tips. If the strain energy near the crack tips exceeds a threshold, the crack extends and the strain-energy distribution is changed again. Thus crack growth is considered to be a process involving the change in the strain-energy distribution in a material.

The process described above can be modelled in a simple manner by using a lattice system. Consider a cubic lattice system, as shown in Fig. 1. We call a cube the grain, and a side of a cube, the grain boundary. The term, grain, is just a spatial unit for a process of the change of strain-energy distribution; it does not stand for a grain used in polycrystals. Crack generation in this system is confined to grain boundaries perpendicular to the system surface.

Suppose that grains in the system have stored their strain energies. Let the strain energies of two adjacent grains (say the ith and the jth grains) be E_i and E_j. If the condition, $E_i E_j \geqslant E_t^2$, is satisfied, we generate a crack on the boundary of the two grains, as shown by the dark plane in Fig. 1. Here E_t is a threshold energy for cracking. When cracking occurs, we release an energy, E_r, from the two grains to the outside of the system; the total strain energy of the system decreases by E_r. After cracking, the strain energies of the two grains both reduce to zero. The remainder, $E_i + E_j - E_r$, of the strain energies of the two grains stored prior to cracking is transferred equally to four grains at the crack tips. This is illustrated in Fig. 1, in which the shaded grains denote the grains to which the strain energy is transferred. If adjacent grains at the crack tips satisfy the cracking condition as a result of this transfer process, the crack extends, and energy release and energy transfer follow. Cracks can continue to grow as long as the cracking condition is satisfied for grains at crack tips.

In the case where two or more boundaries satisfy the cracking condition, we preferentially choose a boundary having the largest values of $(E_i E_j)$. Also, in the case where two or more boundaries have the same largest value, we select one of them at random. Once a crack is generated in the surface layer, the energy transfer is carried out for grains beneath the surface layer, as illustrated in Fig. 1. Thus cracks can penetrate into the interior of the system. In our practical computer simulations, we have incorporated the penetration of cracks by using only grains in the surface layer, in the following manner. The energy transfer is

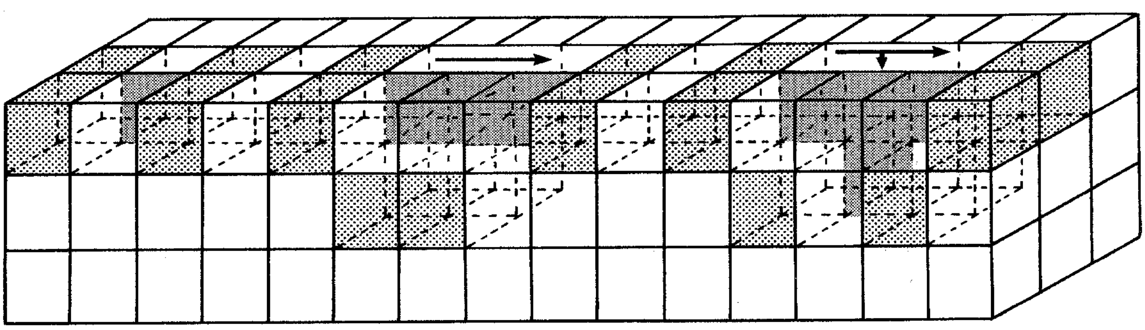

Figure 1 Crack growth in a cubic lattice system. The dark planes represent crack planes, and the shaded cubes (grains) at the crack tips represent the grains to which strain energy is transferred after cracking.

practically carried out only for four grains in the surface layer even after a crack has been generated in the surface layer; any grain boundary in the surface layer is allowed to be cracked two or more times. If any grain boundary has been cracked n times, then we consider that a crack has penetrated by n lattice spacings. Thus the present model can simulate crack growth in three dimensions.

The cracking condition in the present model has been adopted as one possible criterion which incorporates a threshold. The product form, however, is not essential to our simulations. Even if we adopt the summation form, $E_i + E_j \geqslant 2E_t$, as an alternative to the product form, we can obtain similar results of crack patterns. In Section 4, we shall discuss some points supposed in the present model.

2.2. Computer simulation

Simulations of impact fracture in the present model are performed for systems which have stored strain energy prior to an impact shock. To do so we prepare several systems with different distributions of strain energy. This is performed by supplying strain energy spatially at random to the system. We select a grain on the surface at random, and then give a "strain energy", ΔE, to the grain. This storage process is repeated and grains on the surface store their strain energies. If the cracking condition is satisfied at any stage during this process, a crack initiates and the distribution of strain energy changes as a result of the energy transfer described before. When crack growth stops, we go back to the storage process again. While the storage process increases the total strain energy of the system, cracking decreases it. As we will see in the next section, our system settles into a stationary state in which the total strain energy of the system is almost constant. At this stage, we stop the random storage process. By using different values for ΔE, we have prepared several systems with different strain energy distributions.

We are now ready to give an impact shock to the systems. In our simulations, an "impact shock" is regarded as a supply of a much larger energy, E_0, than the threshold energy, E_t, to a central grain on the surface. The supplied impact energy initiates a crack and extends it. We follow the growth of impact cracks according to the rule of changing strain-energy distribution described before. The supplied impact energy dissipates spatially through crack growth, and finally the growth of impact cracks stops. We compare impact damage patterns among systems with different distributions of strain energy stored prior to an impact shock.

Simulations have been performed for a system of 14400 (120×120) grains on the surface. Periodic boundary conditions have been imposed on the sides of the system in the directions parallel to the surface. This number of grains was sufficient for the present investigations; the characteristic features of cracks have not been modified by adopting a larger-sized system of 256×256 grains on the surface. Also the effect of boundary conditions on crack patterns can be disregarded [18].

The values of parameters adopted are as follows. The threshold energy was $E_t = 20$ and the release energy $E_r = 1$. For the storage energy, different values were used: $\Delta E = 0.5$, 1.0, 2.0, 3.0, 4.0 and 5.0. The impact energy was fixed at $E_0 = 1000$. Because the storage process of strain energy carried out prior to an impact shock is a random process, we performed 20 simulation runs for each value of ΔE in order to check statistical errors.

3. Results

3.1. Stationary state

As mentioned in the preceding section, our system settles into a stationary state as a result of the random energy storage and cracking [18]. This behaviour is shown in Fig. 2 for $\Delta E = 1$. The figure exhibits the evolution of the number of cracks, N_C, and the average strain energy per grain, $\langle E \rangle = \sum_i E_i / N_G$, where N_G is the total number of grains on the surface. The upper and the lower parts in the figure show the dependences of N_C and $\langle E \rangle$ on the number of energy storage, N, respectively. At early stages, the strain energy stored by energy storage is much larger than the energy released by cracking. Thus N_C increases slowly and $\langle E \rangle$ increases almost proportionally to N. The system reaches a stationary state at $N_C \sim 6000$. In this state the magnitude distribution of strain energies of grains in the system becomes stable. As a result, $\langle E \rangle$ is almost constant and correspondingly N_C increases proportionally to N, as shown in the figure. In other words, the strain energy stored by energy storage is released from the system by cracking, on average. The fluctuations of $\langle E \rangle$ in the stationary state are due to the alternation of energy storage and cracking.

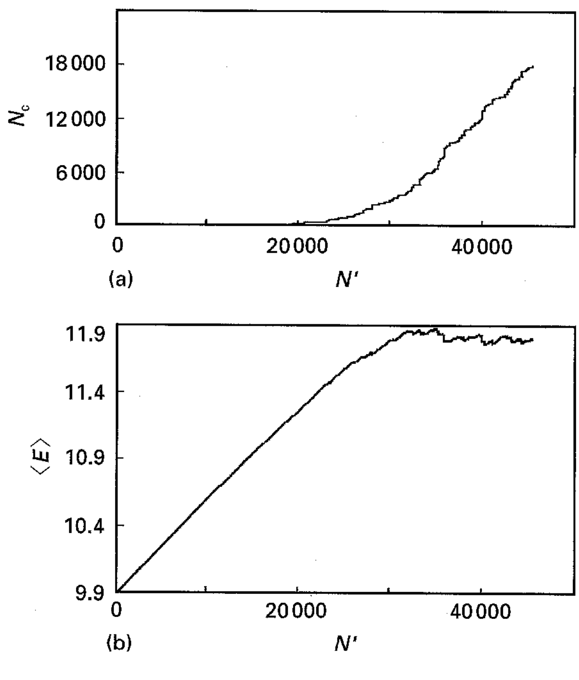

Figure 2 The dependence of (a) the number of cracks, N_c, and (b) the average strain energy per grain, $\langle E \rangle$, on the number of energy storages, N', for $\Delta E = 1$, $E_t = 20$ and $E_r = 1$. Note that the figure shows the dependence after the first crack initiation (the first cracking at $N' = 1$).

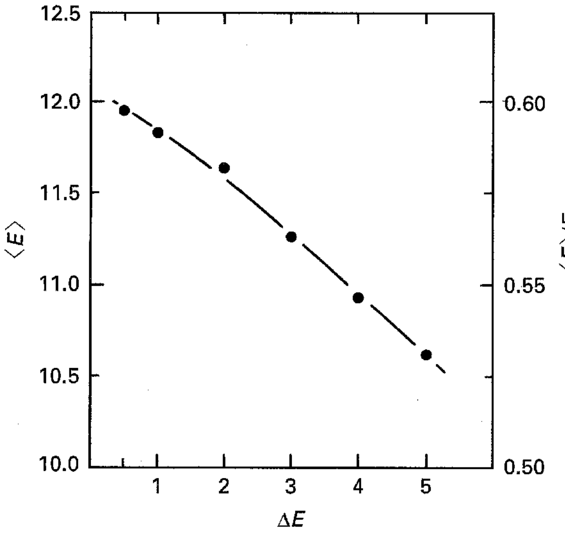

Figure 3 Dependence of the average strain energy per grain in a stationary state, $\langle E \rangle$, on the storage energy, ΔE ($E_t = 20$, $E_r = 1$). The points are the values averaged over 20 runs of simulation and the line is a guide for the eye.

The average strain energy per grain in a stationary state, $\langle E \rangle$, depends on the storage energy, ΔE. Fig. 3 shows the dependence of $\langle E \rangle$ on ΔE. The average strain energy decreases with increasing ΔE. Because a system for a large ΔE has a considerably fluctuating distribution of strain energies among grains, it is settled into a state with a small average energy per grain.

Because a stationary state is reached at $N_C \sim 6000$ for any value of ΔE [18], we have stopped the random storage process at this stage. Typical patterns of cracks in the stationary state are shown in Fig. 4a and b for $\Delta E = 1$ and 5, respectively. The figures show cracks on the surface and their penetrations into the interior of the system; the crack penetration has been represented as a cross-sectional view perpendicular to the surface along the line A–B. Cracks on the surface are relatively rough for $\Delta E = 1$ and fine for $\Delta E = 5$. The depth of crack penetration is at most several lattice spacings for both the cases.

The features of cracks caused by the random energy storage have a close relation to the characteristics of strain-energy distribution in the system. Fig. 5a and b show the magnitude distribution and the spatial distribution of strain energies of grains in the stationary states for $\Delta E = 1$ and 5, respectively. The spatial distribution represents strain energies of grains along the line A–B in the surface crack pattern of Fig. 4. The system for $\Delta E = 1$ has a magnitude distribution which is concentrated around the average energy. The distribution of the system for $\Delta E = 5$ is considerably fluctuating in magnitude and also in space. The features of surface cracks, as seen in Fig. 4a and b, correlates with the characteristics of strain-energy distribution in Fig. 5a and b. In a system exposing relatively fine cracks, strain energies of grains are distributed with considerable fluctuations in magnitude and in space. Furthermore, the characteristics of strain-energy distribution dominate the impact damage pattern, as will be shown below.

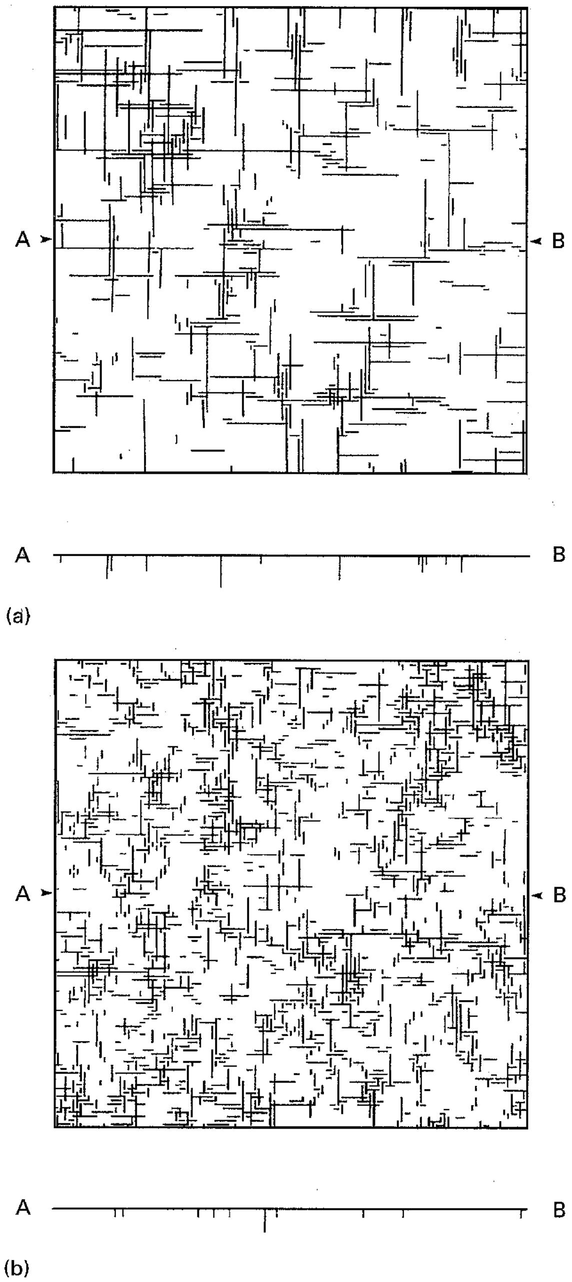

Figure 4 Surface crack pattern and crack penetration in a stationary state (before an impact shock) for the systems with $E_t = 20$ and $E_r = 1$: (a) $\Delta E = 1$; (b) $\Delta E = 5$. The crack penetration has been shown as a cross-sectional view perpendicular to the surface (along the line A–B). The depth scale is twice the lattice spacing on the surface.

Prior to changing the subject to impact damage, we take up two systems with specific distributions of strain energies of grains. One is a system whose strain-energy distribution is almost uniformly wide in magnitude and randomly fluctuating in space, as shown in Fig. 6a. This system has been obtained by adopting a large value for the release energy, $E_r = 20$ ($\Delta E = 1$, $E_t = 20$); in this system, cracking releases half of the strain energies of grains on both sides of a crack from the system. The corresponding pattern of cracks is shown in Fig. 7a. The pattern is composed of many short cracks which are distributed almost uniformly. This is a consequence of the fact that cracking in this case is dominated mostly by random energy storages because crack extension is restrained by a large release

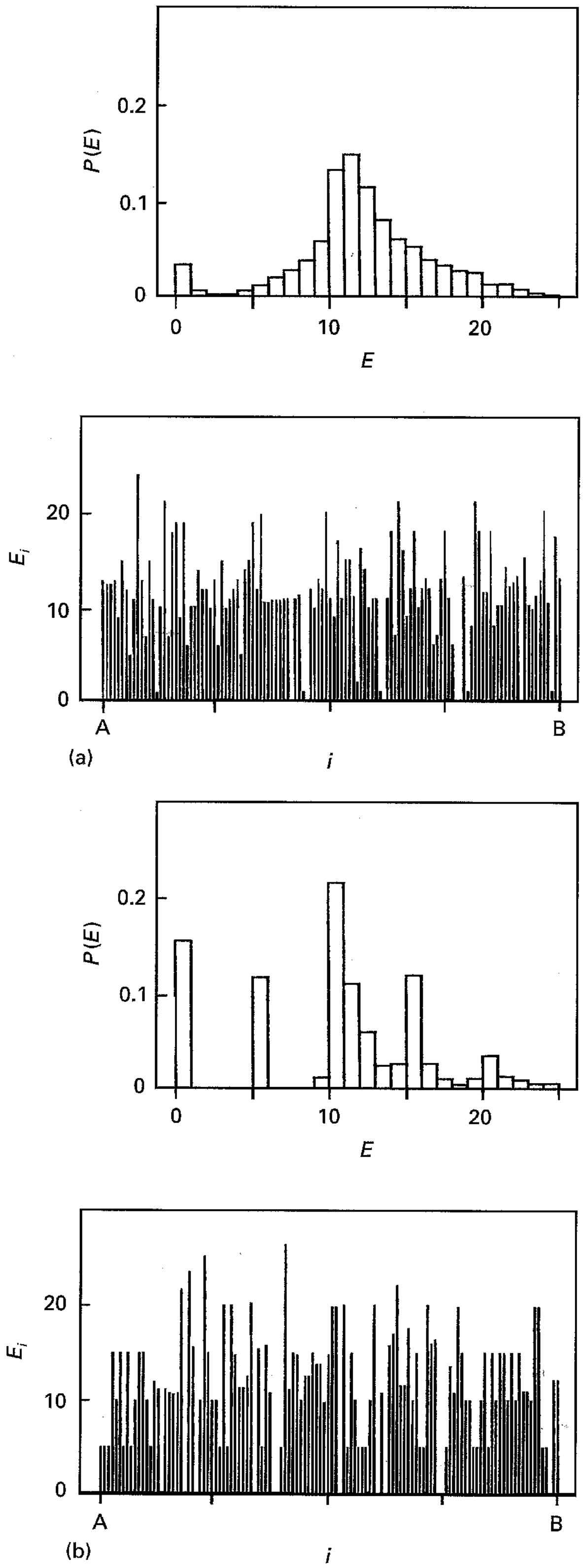

Figure 5 Magnitude distribution (upper part) and spatial distribution (lower part) of strain energies of grains for the systems with $E_t = 20$ and $E_r = 1$: (a) $\Delta E = 1$; (b) $\Delta E = 5$. The spatial distribution has been shown for grains along the line A–B in Fig. 4.

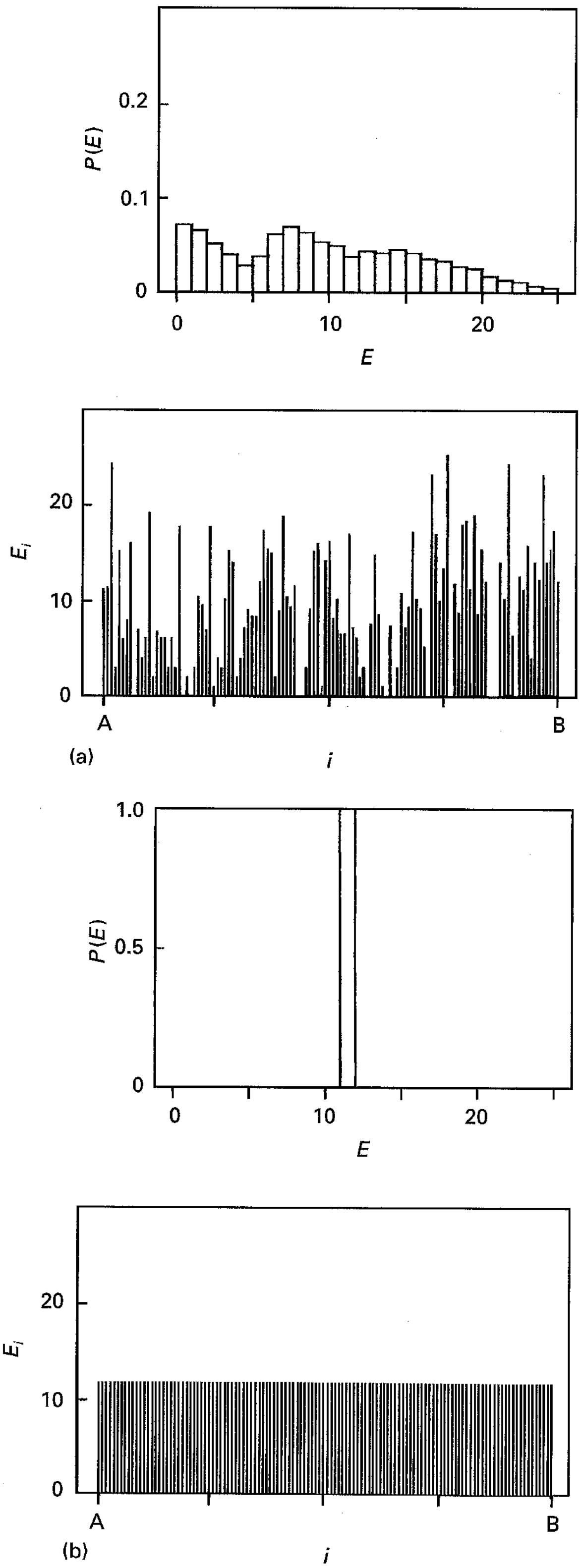

Figure 6 Magnitude distribution (upper part) and spatial distribution (lower part) of strain energies of grains: (a) a system with $E_r = 20$; (b) a system in which all grains have the same strain energy. The spatial distribution has been shown for grains along the line A–B in Fig. 7.

energy. Another system with a specific distribution of strain energies of grains is shown in Fig. 6b. This system has been obtained, not by the random storage of strain energy, but by forcing strain energy to distribute uniformly in space; in this case there are no cracks, as seen in Fig. 7b. In this system, all grains on the surface have the same strain energy as the average energy of the system of Fig. 5a. In the next subsection we will show impact damage for these two systems as well as for the systems of Fig. 5a and b.

3.2. Impact damage

We have supplied an impact energy, $E_0 = 1000$ to a central grain on the surface of each system in a

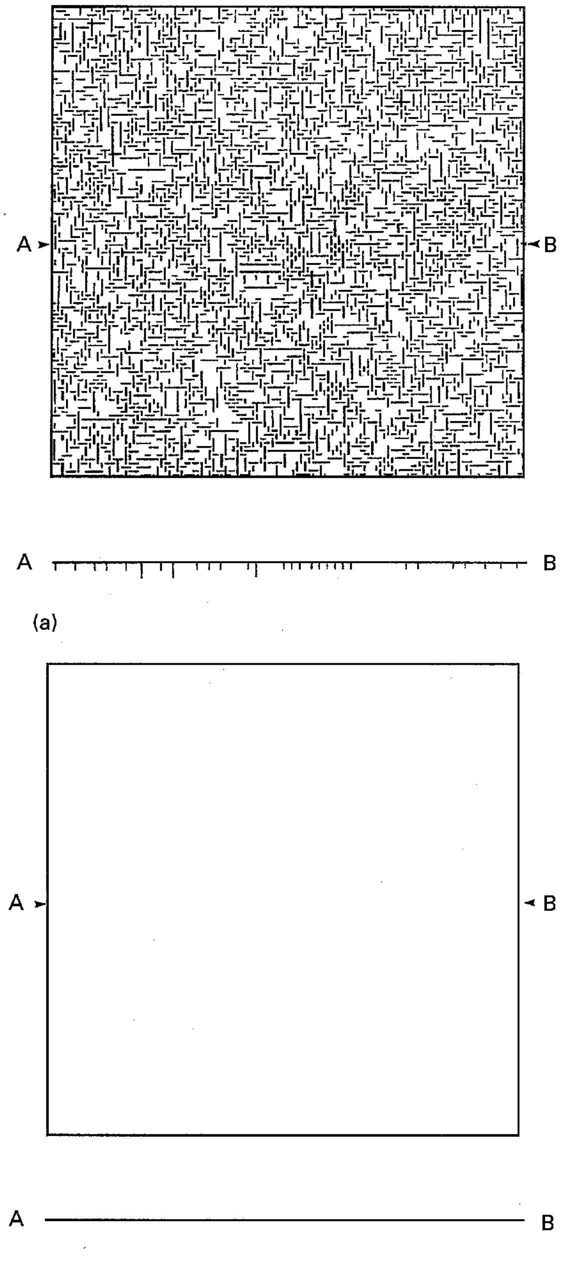

Figure 7 Surface crack pattern and crack penetration (before an impact shock): (a) a system with $E_r = 20$; (b) a system in which all grains have the same strain energy.

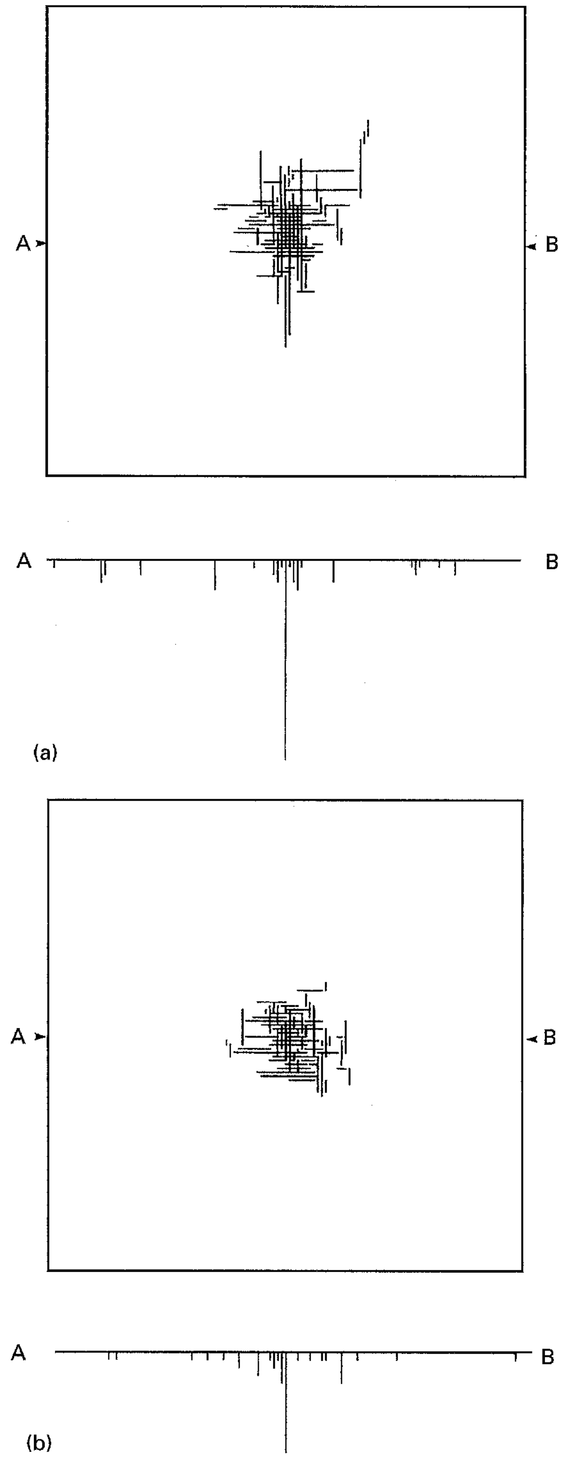

Figure 8 Impact cracks on the surface and crack penetration under $E_0 = 1000$ for the systems of Fig. 5: (a) $\Delta E = 1$; (b) $\Delta E = 5$. Only the cracks caused by an impact shock are shown on the surface. See also the caption of Fig. 4.

stationary state. The supply of the impact energy produces different patterns of impact cracks depending on the characteristics of the system. Fig. 8a and b show impact cracks for the systems of Fig. 5a and b, respectively. The upper part in the figure shows the surface pattern of only the cracks caused by the impact energy; the total number of cracks is obtained as the superposition of the two surface crack patterns of Figs 4 and 8. Impact cracks for $\Delta E = 1$ extend considerably on the surface and penetrate deeply into the interior. Impact cracks for $\Delta E = 5$ are limited around an impact point on the surface and their penetrations are relatively shallow.

The detailed aspect of impact damage, as a matter of course, depends on the state of the system before impact shock. However, the characteristic features of impact damage, as mentioned above, are not modified by different runs of the random storage. Figs 9 and 10 show two examples of surface patterns of impact cracks resulting from different runs for $\Delta E = 1$ and 5, respectively. Impact damage for $\Delta E = 1$ extends considerably on the surface. Impact damage for $\Delta E = 5$ is localized around an impact point on the surface.

Impact cracks for the systems of Fig. 6a and b are shown in Fig. 11a and b, respectively. In the case of a large release energy of Fig. 6a, impact damage is slight, as expected. In the case of a spatially uniform distribution of strain energies of grains of Fig. 6b, the

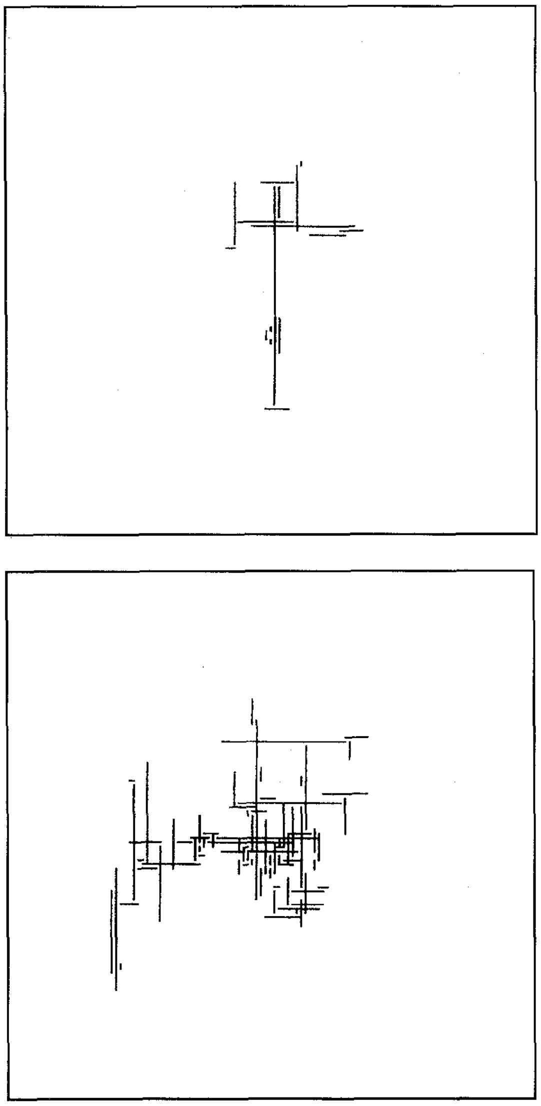

Figure 9 Different impact damage patterns on the surface under $E_0 = 1000$ for the systems with $\Delta E = 1$. These patterns have been obtained by different runs of simulation.

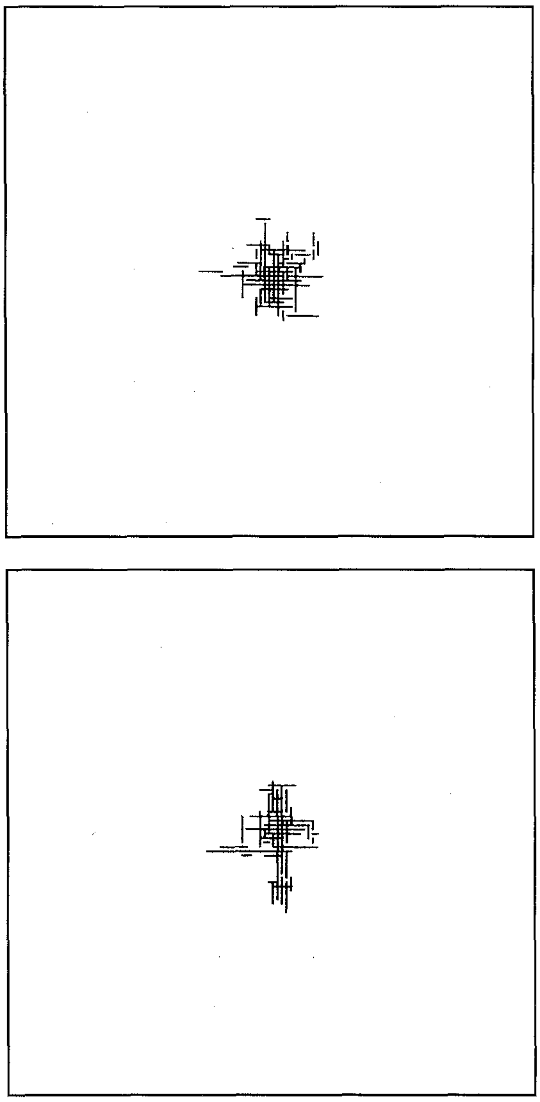

Figure 10 Different impact damage patterns on the surface under $E_0 = 1000$ for the system with $\Delta E = 5$. These patterns have been obtained by different runs of simulation.

impact damage pattern is only a straight line. In this case, an initial crack extends with one rush and penetrates deeply.

The impact damage pattern is dominated by the characteristics of strain-energy distribution stored prior to an impact shock. For a system having a concentrated magnitude distribution of strain energy, as seen in Figs 5a or 6b, an impact shock has produced remarkable extension and penetration of impact cracks, as shown in Figs 8a, 9, or 11b. The strain-energy distribution in these systems is narrow in magnitude and relatively uniform in space. Then impact cracks tend to extend because there are many grains having almost the same strain energy. If a system has a considerably fluctuating distribution of strain energy, as seen in Figs 5b or 6a, impact cracks do not extend on the surface and do not penetrate remarkably, as shown in Figs 8b, 10, or 11a. Because, in this case, many grains having a small strain energy are scattered at random, impact cracks are likely to be arrested. Thus the features of impact damage reflect the characteristics of strain-energy distribution stored prior to an impact shock.

The quantitative evaluation of impact damage is shown in Fig. 12. The figure shows the dependence of the penetration depth of impact cracks on ΔE; the points are the values averaged over 20 runs of simulation for each value of ΔE. As ΔE increases, the penetration depth becomes shallow. This is attributed to the fact that a larger ΔE leads to a stationary state with a smaller average energy, as shown in Fig. 3, and that the distribution of strain energies of grains is more fluctuating. The fluctuation of strain energies among grains is favourable for obstructing crack penetration.

The total energy released from the system by impact cracks, depends on ΔE through the characteristics of strain-energy distribution. We have defined the energy release rate due to impact cracks, R, as $R = (E_{after} - E_{before})/E_0$, where E_{before} and E_{after} are the total strain energies of a system before and after an impact shock, respectively. If R is positive, part of a supplied impact energy, E_0, is stored as a residual strain energy. On the contrary, if R is negative, the system releases larger energy than the supplied impact energy. Fig. 13 shows the dependence of R on ΔE. As

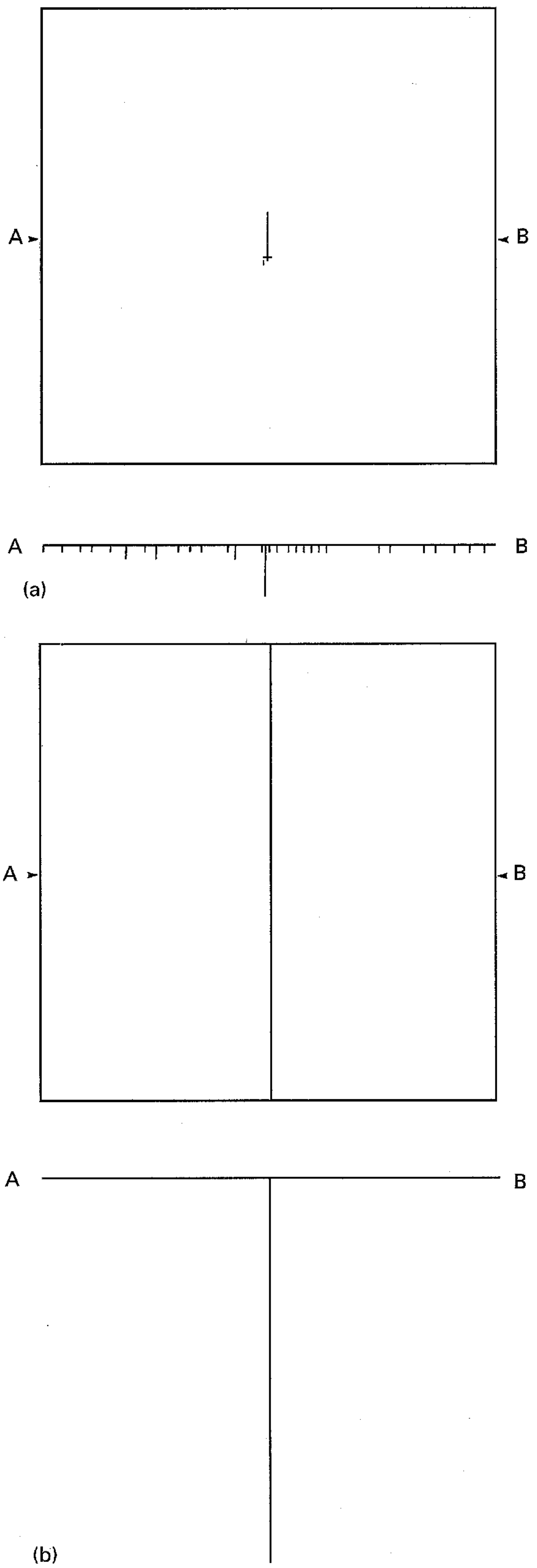

Figure 11 Impact cracks on the surface and crack penetration under $E_0 = 1000$ for the systems of Fig. 6: (a) a system with $E_r = 20$; (b) a system in which all grains have the same strain energy. Only the cracks caused by an impact shock are shown on the surface.

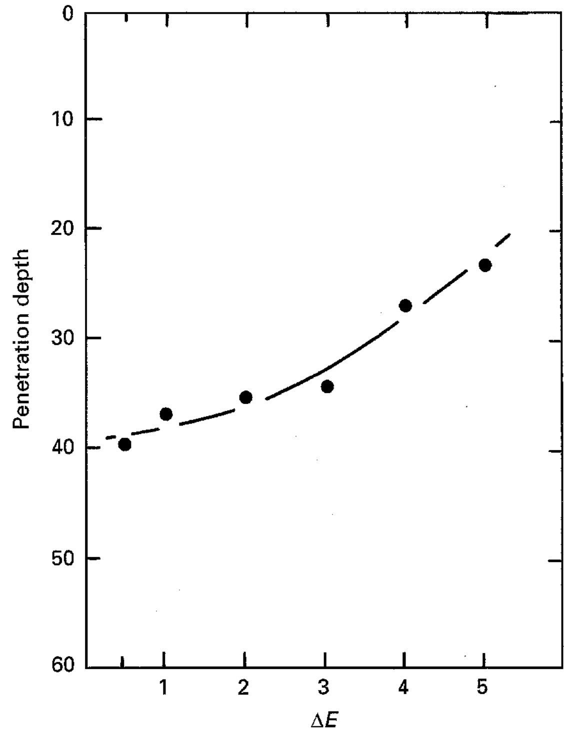

Figure 12 Dependence of the penetration depth of impact cracks on the storage energy, $\Delta E(E_t = 20, E_r = 1, E_0 = 1000)$. The points are the values averaged over 20 runs of simulation and the line is a guide for the eye.

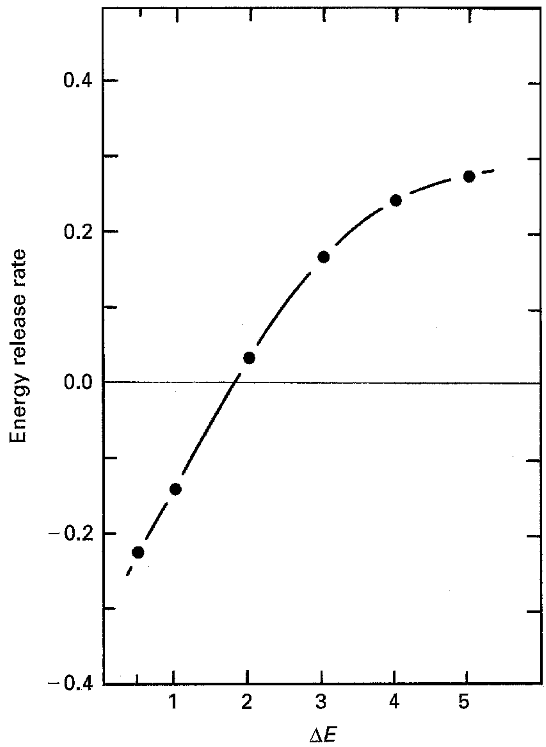

Figure 13 Dependence of the energy release rate on the storage energy, $\Delta E(E_t = 20, E_r = 1, E_0 = 1000)$. The points are the values averaged over 20 runs of simulation and the line is a guide for the eye.

ΔE decreases, the energy release rate decreases and changes its sign from plus to minus. In a system for a small ΔE, therefore, large energy is released from the system by an impact shock. As a result, impact cracks in such a system penetrate deeply, as seen in Fig. 8a.

4. Discussion

The present model simulations have been simplified by regarding crack growth as a process involving the change of strain-energy distribution. If we consider a detailed aspect of crack growth in a specified material, we would have to investigate stress or strain field on the basis of conventional models. However, global features of a crack pattern should be understood to some extent from the viewpoint of strain-energy dissipation. Therefore we have explored a simple model for crack growth in the present study. Thus parameters in our model do not correspond directly to parameters that are used in the elasticity theory and fracture mechanics. The results of simulations, however, have some implications in considering the nature of impact fracturing, as discussed below.

The present simulations correspond to impact fracture of materials that contain some cracks before experiencing an impact shock. In practical cases, various materials are often exposed to an environment that cause defects and micro-cracks, and then experience an impact shock. For example, materials are often exposed to continual irradiation of particles, such as atoms, molecules, ions, neutrons, X-rays, or γ-rays. These situations produce radiation damage near the surface of the material, such as defects, impurities, or cracks, which cause strain energy to be distributed at random near the surface. Thermal cycling or thermal shock on a material produces spatially random stresses and strains in the material. Spatial randomness of stress and strain in this case may be ascribed to various types of disorder in the material itself or to thermal fluctuations of the environment. These random stresses and strains also cause strain energy to be distributed at random near the surface. Heat-resisting materials used for space craft are one typical example in these irradiational and thermal environments. Chemical reaction, such as alkali-aggregate reaction in concretes, is also an important example which causes spatially random strain energy. Fracture in these irradiational, thermal, or chemical environments corresponds qualitatively to cracking by the random storage of strain energy in the present simulations. Therefore, the present simulations of impact fracture give some implications in regard to the nature of impact fracturing of materials which contain cracks caused by environmental influences.

Suppose that there are some materials that have exhibited different crack patterns on the surface. A material which has exhibited many fine cracks, like the system of Fig. 4b, is expected to show limited impact damage, as inferred from Fig. 8b. Such a material should have a large spatial fluctuation of strain energy, as seen in Fig. 5b, and therefore is likely to arrest crack extension due to an impact shock. In particular, if a material has exhibited fine cracks distributed uniformly on the surface, as seen in Fig. 7a, the material should have a strong resistance to an impact shock, as inferred from Fig. 11a. A material which has exhibited a rough pattern of cracks, like the system of Fig. 4a, will receive severe impact damage, as seen in Fig. 8a. Residual strain energies in such a material are inferred to distribute almost uniformly, as seen in Fig. 5a. This results in a deep penetration of impact cracks that causes fragmentation of the material; the material is in danger of disastrous failure by an impact shock. Thus, the present simulations give information about the material evaluation and the material resistance to impact shock.

Figs 12 and 13 show the effect of ΔE on the characteristics of impact cracks. For a small ΔE, impact cracks have penetrated deeply and a large energy has been released from the system by an impact shock. From these results, it is inferred that an impact shock induces severe damage in a material which was exposed to an environment giving small strain energies for a long time. On the contrary, for a material which was exposed to an environment causing a fluctuating strain-energy distribution, an impact shock is expected to be absorbed appreciably. Thus the present simulations give some suggestions in predicting the nature of impact fracturing.

We have carried out simulations using a cubic lattice system. The direction of crack extension is, as a matter of course, restricted by the lattice shape used for the simulations. However, the global features of cracks are not dependent on the lattice shape; simulations based on a trigonal prism lattice showed the similar features of crack patterns [19]. Therefore, a cube in the present lattice is just a spatial unit for carrying out the transfer of strain energy. The global features of cracks are governed by the spatial characteristics of strain-energy distribution in the system. In the present model, a stochastic variation of the threshold energy, E_t, has not been taken into account. Consideration of this variation results in more fluctuating patterns of cracks in space than the present results. However, the relative difference in the crack pattern and the crack penetration between different values of ΔE is not modified qualitatively.

In the present model, we used some simple rules regarding the cracking condition and the energy transfer. We have used the product form, $E_i E_j \geqslant 2E_t$, as a cracking condition. We have incorporated the existence of a threshold for cracking in this form. As mentioned before, however, the product form is not vital in the present simulations. As for the energy transfer, we have transferred strain energy equally to four grains at crack tips. Although this rule was adopted as a simple one, the global features of cracks revealed in the present rule have not been modified appreciably by other similar rules. We have fixed the value of the release energy, E_r, except for the system of Fig. 6a, in order to investigate mostly the effect of the storage energy, ΔE, on impact damage. The release energy corresponds to energy expended by forming a crack plane, emission of acoustic waves and plastic deformation. Because, in the present simulations, the release energy is much smaller than the threshold energy, the present model simulation corresponds to crack growth in brittle materials in which the effect of plastic deformation on fracture is not vital.

The interaction between cracks is an important factor in predicting crack growth. In terms of stress and strain fields, cracks are considered to interact with each other through these fields. In the present simulations, the interaction between cracks has been taken into account through the transfer of strain energy to grains at crack tips; cracks interact with each other only through grains at crack tips. The effect of longerrange interaction on the global features of cracks will be left for future study.

The present model is not inconsistent with the Griffith energy-balance concept for brittle fracture [2]. In the Griffith theory, a crack extends when a decrease of strain energy due to the formation of a new crack plane overcomes an increase of the surface energy of the new crack plane. In other words, a crack grows if a material gains in an energetic sense by forming a new crack plane. Then this criterion is represented usually as a critical stress at which a crack extends. In our simulations, a crack initiates or extends when strain energy exceeds a threshold, and an energy, E_r, is released from the system. Therefore, the system gains in an energetic sense if strain energy locally reaches a critical value. We have introduced a threshold energy, E_t, as this critical energy. Although the present model is not based on stress or strain field, energetics in crack growth is on the same basis as conventional approaches.

Impact fracture is a dynamic phenomenon. An impact shock in the present model has been regarded as a supply of a large strain energy to a grain on the surface. The model, as it stands, does not include dynamic aspects of fracture process, such as shock waves [22]. However, we here notice a non-equilibrium aspect in impact fracture. When a material is subjected to an impact shock, the material stores a large strain energy within a local region in a very short time. The material is energetically far from in equilibrium. Then fracture in this case is a process by which the material approaches equilibrium through crack initiation and extension. In the present simulations of impact fracture, we have supplied locally a much larger energy than a threshold energy for cracking to a system, and have followed how the impact energy dissipates through crack growth. In this sense, the present approach simulates this dissipation process of supplied impact energy. Specific aspects associated with dynamic fracture [23] will be left for future study.

5. Conclusion

We have shown that a simple model simulation of impact fracture reveals different patterns of impact damage. Crack growth was modelled as a dissipation process of strain energy using a cubic lattice system. By supplying a large strain energy to the system surface, the growth of impact cracks has been followed for systems which have different distributions of strain energy stored prior to the impact shock. The results of simulations are summarized as follows. The features of impact damage are dominated by the strain-energy distribution stored prior to an impact shock. In particular, a system having a relatively uniform distribution in space shows a considerable extension and a deep penetration of impact cracks.

The results of simulations have given some information about the material evaluation and the material resistance to impact shock. From the crack features that a material has exposed, we could infer the characteristics of strain-energy distribution and the nature of impact damage before the material is subjected to an impact shock. The crack pattern on the surface is not only a trace of the past influences on a material, but also a significant indication of the present characteristics of the material. It also provides clues for predicting the nature of impact fracturing. In this sense, the global evaluation of crack patterns should be taken into consideration in the fracture study.

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