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Fundamental problems in brittle fracture: unstable cracks and delayed breaking

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Note presented by Jean-Baptiste Leblond and Yves Pomeau.

Abstract This presents a short review on two problems where brittle fracture is involved. In the first one, a hot glass plate is subject to a local stress when drowned into a cold bath. In the region of transition between the cold and hot side, large stresses build up, that can be related accurately to the various coefficients typical of the plate material, heat dilation coefficient, heat conductivity, Young's modulus, etc. Thanks to thais, one can compare well the experimental results and the theoretical predictions based on the Griffith criterion for the propagation of a straight crack, and for its instability against an undulating mode. In the other problem, one looks at the delay before a bent 2D crystal breaks: this (very long) delay is interpreted as the time required for homogeneous nucleation of a critical Griffith nucleus in a region of the crystal under extension. Although it agrees fairly well with some experimental data, other experimental facts are required to complicate the model by considering a multistep nucleation process. ***To cite this article: Y. Pomeau, C. R. Mecanique 330 (2002) 249–257.*** © 2002 Académie des sciences/Éditions scientifiques et médicales Elsevier SAS

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Deux problèmes de la rupture fragile : des cracks instables et la fracture à retardement

Résumé Ceci présente une revue courte de deux problèmes impliquant la rupture fragile. Dans le premier, une plaque de verre chauffée est plongée dans un liquide froid. Dans la région de transition entre les parties froide et chaude de grandesz contraintes existent. Elles peuvent être reliées de façon précise aux différents coefficients typiques du matériau de la plaque : dilatation thermique, conductivité thermique, module d'Young, etc. Grace à cela on peut comparer les résultats expérimentaux et la théorie basée sur le critère de Griffith pour la propagation d'un crack droit puis pour son instabilité par rapport à un mode d'ondulation. Dans l'autre problème, on examine le delay au bout duquel un cristal 2D courbé se brise : ce delai (très long) est interprété comme le temps nécessaire à la nucléation d'un noyau critique de Griffith dans la région du cristal en extension. Bien que cette théorie soit en accord avec plusieurs des données expérimentales, d'autre données exigent de compliquer le modèle en considérant une nucléation par étapes. ***Pour citer cet article : Y. Pomeau, C. R. Mecanique 330 (2002) 249–257.*** © 2002 Académie des sciences/Éditions scientifiques et médicales Elsevier SAS

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1. Introduction

This reports recent work made by the author and a collaborator, M. Adda Bedia, on two fundamental questions of brittle fracture: is it possible to check quantitatively theories of crack propagation a in stressed solid, and how long does it take for a piece of stressed crystal to break? Both questions have received a lot of attention over the years, although the second one seems to have been a bit left aside by the community of solid state physics. This summarizes a presentation made at the 'Journée de la rupture', Paris, Académie des sciences, 26 February 2001.

The work on the first question [1] was motivated by an interesting experiment by Yuse and Sano [2] to be described below, and that yielded clean and interesting results on crack propagation: a stripe of heated glass is pulled in a cold liquid bath, with a dent at its lower side. Because of the heat dilation, a band of non uniform temperature was under thermal stress on the plunging plate near the liquid surface, and under appropriate conditions it was able to support the propagation of a crack: this crack relaxes the mechanical stress there and so can propagate if the Griffith–Irwin criterion is fullfilled (meaning that the release of elastic energy overcomes the energy needed to create a new surface on both sides of the crack). We felt that the problem was of interest because of the existence of a well defined control parameter, (practically) the speed of descent of the plate in the cooling liquid and because the crack propagation was quasistationary (that is at speeds considerably less than any speed of propagation of elastic disturbances in the plate). Indeed, the velocity of descent matters because it does change the stress distribution and intensity, not because it introduces any time dependence in the crack motion itself. Another interesting experimental observation is the occurrence of an instability in the crack propagation beyond a secondary speed threshold. This can be explained as well in the Griffith–Irwin framework and by using the principle of local symmetry of Cotterell–Rice. It is an interesting application of the concepts of solid state mechanics, where one can predict an instability without ever writing a dynamical equation for the problem in hand, contrary to what one would do in fluid mechanics, for instance, following Rayleigh's ideas. This question of the crack propagation in thermally stressed plate is the matter of Section 2 below.

The work on the second question has been published in the Comptes-Rendus [3] and was also motivated by an interesting experimental observation by Bercegol and Meunier [4,5]. They managed to crystallize a monolayer floating on water under pressure, and to see through a special microscope the needle-like crystals so produced. As those crystals were usually quite thin and long (length in the millimeter range, width in the tenth of millimeter range); they could be bent in a controlled way to measure their elastic parameters. Those 2D crystals, when bent, were observed to break after times typically of the order of forty seconds. Such times are very long compared to any molecular time scale, in the 10^{-12} second range in the usual condition of condensed matter at room temperature. The explanation proposed for this huge difference of time scales relied on the existence of a very small Arrhenius factor related to the imposed stress. However, this theory was only partly successful to explain the observations. Later observations had shown that actually the breaking process was not a Markov process, that would correspond to single barrier crossing with a single Arrhenius factor. This required us to change the theory to reconcile the very small Arrhenius factor together with the non-Markovian transition to breaking. This is discussed in Section 3 below. Section 4 is devoted to summary and conclusions.

2. Breaking of stressed plate: onset of crack propagation and of crack undulation

The experiment of Yuse and Sano [2] has been briefly described in the introduction. A hot glass plate is pulled into a cold bath at a slow and constant speed V (Fig. 1). The control parameters are the pulling velocity V, the strip width $2b$ and the temperature drop between the heater and the cold bath, ΔT. Typical order of magnitudes are $V = 3$ mm·sec^{-1}, $\Delta T = 70$ K and $b = 1.2$ cm. The thickness of the plate is in the fraction of a millimeter range and does not play any role, as the temperature distribution is almost uniform across the plate. When V, ΔT and b are small, the strip does not break: more precisely the dent made in the middle of the lower side of the plate does not start a propagating crack. By increasing essentially b

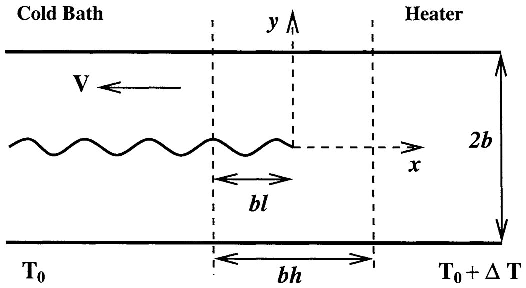

Figure 1. Plate geometry; see [1].

or ΔT, a centered straight crack branches off the initial dent at some threshold value, and stays fixed in the lab frame, near the surface of the cooling liquid. Its speed of propagation in the frame of the strip is $-V$, that is upward. By further increasing these parameters the straight crack becomes unstable and begins to undulate. Then the fracture follows an oscillating path, but the crack tip remains near the surface of the cooling bath. At still higher pulling speeds, other changes of morphology of the crack, such as secondary branching, occur. We shall not consider them here.

2.1. Propagation of the straight crack

To analyse this experiment, we proceed in two steps. First, we show that the stressed area on the strip, near the surface of the cooling bath, can support crack propagation according to the Griffith–Irwin criterion if a certain dimensionless combination of parameters exceeds a threshold value. Among the parameters lies the Griffith fracture energy Γ, a material constant. We shall closely follow [1], to which we refer the reader interested by a more detailed analysis. The coordinate system is such that x is in the vertical direction, although y is the horizontal coordinate. The temperature field of the plate is $T_l(x)$, the cold bath being at $x \leqslant l$, the length l is so chosen that the tip of the crack is at $x = 0$. The temperature field is stationary in the lab frame, and it is a solution of the equation

$$\nabla^2 T_l(x) + P\frac{\partial T_l(x)}{\partial x} = 0$$

where $P = \frac{bV}{D}$, is a dimensionless number, D being the heat diffusion coefficient in the solid, and b, half plate width, has been taken as unit length. Furthermore, we assume the plate to be infinitely long, so that the temperature $T_l(x)$ tends to 1 as x tends to $+\infty$ (the hot size), and to zero as x tends to $-\infty$ (cold side). Therefore the temperature field inside the strip is:

$$T_l(x) = \left(1 - \mathrm{e}^{-P(x+l)}\right)\theta(x+l) \tag{1}$$

where $\theta(\cdot)$ is the Heaviside step function. Once the temperature field is known and by solving the equation of thermoelasticity, one can compute the stress field inside the strip. The strain and stress are related to the temperature field by the equation:

$$\Sigma_{ij} = \frac{1}{1-\nu^2}\left[(1-\nu)E_{ij} + \nu E_{kk}\delta_{ij} - (1+\nu)T_l(x)\delta_{ij}\right] \tag{2}$$

where Σ_{ij} is a Cartesian component of the 2D stress tensor, although E_{ij} is a Cartesian component of the 2D strain. In Eq. (2), rescaling has been made so that Σ is measured in units $\alpha_T \Delta T E$, ΔT imposed temperature difference across the strip, α_T coefficient of thermal dilation and E Young's modulus. Furthermore, here and elsewhere we assumed as usual summation over like indices. The equations of elasticity for a straight crack take the usual static form, since dynamical effects (or equivalently the inertia contribution to the stress balance) are negligible at the speeds under consideration. They can be written:

$$\frac{\partial \Sigma_{ij}}{\partial x_j} = 0 \tag{3}$$

and

$$\nabla^2\big(\Sigma_{ii} + T_l(x)\big) = 0 \tag{4}$$

the boundary condition being that the stress disappears on the free surface of the crack $\Sigma_{ij} n_j = 0$, where **n** is the unit vector normal to the crack edge. Similarly on the lateral side of the strip $\Sigma_{yy}(x, \pm 1) = \Sigma_{xy}(x, \pm 1) = 0$. The information on the stress distribution is used to determine if crack propagation is possible or not by using the energy criterion of Griffith. It states that the crack is at a critical value of incipient growth if the reduction in the stored elastic energy W_{el} associated to a small virtual crack advance ds from that state is equal to the fracture energy Γ:

$$-\frac{\partial W_{\mathrm{el}}}{\partial s} = \Gamma \tag{5}$$

with

$$\frac{\partial^2 W_{\mathrm{el}}}{\partial s^2} < 0 \tag{6}$$

With the quantities introduced, W_{el}, the thermoelastic energy per unit thickness of the strip, is:

$$W_{\mathrm{el}} = Eb^2(\alpha_T \Delta T)^2 \widetilde{W} \tag{7}$$

where $\widetilde{W}$ is the following dimensionless quantity:

$$\widetilde{W} = -\frac{1}{2}\int_{-\infty}^{+\infty} \mathrm{d}x\, T_l(x) \int_{-1}^{+1} \mathrm{d}y\, \Sigma_{ii}(x, y) \tag{8}$$

At this step we have enough information to give the relevant parameters, that are the dimensionless combination(s) that rule the problem. First there is the ratio of the plate width to the penetration depth of the temperature field on the plate. This is the quantity denoted P before that is equal to bV/D. In the experiments, this is typically a large number, a few tens. The other quantity is the ratio of the available elastic energy to the fracture energy, namely $Eb\,(\alpha_T \Delta T)^2 / \Gamma$. When this is large, the crack can propagate and it cannot when this is small.

The case of a straight crack can be analysed explicitly. The equations for the stress can be written:

$$\frac{\partial \sigma_{ij}}{\partial x_j} = 0 \tag{9}$$

and

$$\nabla^2\big(\sigma_{ii} + T_l(x)\big) = 0 \tag{10}$$

The boundary conditions are

$$\sigma_{yy}(x,1) = \sigma_{xy}(x,1) = \sigma_{xy}(x,0) = 0, \quad \sigma_{yy}(x,0) = 0 \quad \text{for } x \leqslant 0, \quad u_y(x,0) = 0 \quad \text{for } x \geqslant 0,$$

some of the boundary conditions coming from the symmetry of the problem (for instance $\sigma_{xy}(x,0)=0$ accounts for the fact that σ_{xy} is odd with respect to y for a straight crack). Eqs. (9), (10) can be solved in Fourier transform in the y direction. The Wiener–Hopf technique permits us to impose the boundary condition on $y=0$, which finally gives the sought after expression for the thermoelastic energy $\widetilde{W}$:

$$\widetilde{W}=\widetilde{W}_0(P)-\int_{-\infty}^{l}\mathrm{d}x\, g_l^2(x) \tag{11}$$

where the two functions $W_0(P)$ and $g_l(x)$ are known explicitely:

$$\widetilde{W}_0(P)=\int_{-\infty}^{+\infty}\frac{\mathrm{d}k}{2\pi}\left[1-\frac{4\sinh^2(k)}{k(2k+\sinh(2k))}\right]\frac{P^2}{k^2(k^2+P^2)} \tag{12}$$

and

$$g_l(x)=\int_{-\infty}^{+\infty}\frac{\mathrm{d}k}{2\pi}D_0(k)F^+(k)\,\mathrm{e}^{-\mathrm{i}kx} \tag{13}$$

where $F^+(k)$ is related to

$$F(k)=k\frac{\sinh^2 k-k^2}{\sinh 2k+2k}$$

as $F(k)=F^-(k)/F^+(k)$ where $F^+(k)$ and $F^-(k)$ have no poles or zero for $\mathrm{Im}(k)>0$ and $\mathrm{Im}(k)<0$, respectively. Finally,

$$D_0(k)=2\frac{-P}{\mathrm{i}k(\mathrm{i}k-P)}\frac{(1-\cosh k)(\sinh k-k)}{\sinh 2k+2k}$$

The condition of propagation of a straight crack is derived from the Griffith energy criterion. The stress intensity factor K_I is just given by the derivative with respect to l of the thermoelastic energy:

$$-\frac{\partial\widetilde{W}}{\partial l}=K_I^2 \tag{14}$$

The quantity K_I so defined is a function of l and P. Since we are interested in a threshold effect, that is by a condition that K_I^2 gets bigger than the fracture energy Γ, we shall look at its maximum value as a function of l, that becomes a function of P only. Let $K_I^{(s)}(P)$ be this maximum value. Therefore the condition for propagation of a straight crack becomes

$$K_I^{(s)}(P)\geqslant\frac{\sqrt{\Gamma/(Eb)}}{\alpha_T\,\Delta T} \tag{15}$$

Notice the geometry of the experiment is such that the stress intensity factor is concentrated in a rather narrow band where the temperature varies and so is the strain. Therefore, when the condition (15) is satisfied, there are two positions (two values of l) where the Griffith condition is satisfied. One is unstable, because by shifting the crack upward, the elastic energy derivative is still decreased, although the other one, where the elastic energy decreases by shifting the crack, is the physically relevant stable crack position.

Before considering the next problem, that is the transition from a straight to an undulating crack, it is relevant to notice that the detailed analysis of the straight crack that we just sketched shows that it is not possible to take the limit of an infinitely wide plate (b infinite): in this limit, one cannot find an expression for the stress distribution in the plate, that depends crucially on the finite width of the plate. This is because the stress distribution depends in a nontrivial way on the geometry, here and elsewhere.

2.2. Undulation of the crack

One very spectacular manifestion of the crack instability in this type of experiment is the occurrence of undulations. The occurrence of instabilities in crack propagation is a well-known phenomenon, but usually associated to crack propagating at large speeds, of the order of the Rayleigh speed. Here on the contrary the dynamical effects of the propagation on the elastic phenomena are quite negligible, since the velocity is order of magnitudes less than the one of elastic waves. Furthermore, the observed undulations are very regular and even very close to sinusoidal near threshold conditions.

The occurrence of these undulations may be described rather vaguely as showing the existence of an instability in the propagation of a straight crack. The trouble with this statement is that there is no real time dependent equation for the dynamical stability of a crack solution with respect to a given perturbation. Therefore, one has to rely on a strategy different of the one usually followed in stability studies.

We proceed in two steps: first we assume the crack slightly undulated, with an arbitrary small amplitude. Let $y(x)$ be the position of the crack. A straight crack is such that $y(x) = 0$, with our choice of coordinates. A small deviation out of the straight line is represented by a function $y(x) = A\sin(\omega x)$, with $|A| \ll b$. This undulation changes the stress field in the plate. In particular it yields a nonzero K_{II} contribution to the stress intensity factor near the crack tip, that was absent by symmetry for a straight crack. This mode-II component of the stress represents the amount of shear imposed on the crack. According to the general principle of local symmetry, the crack will change its path in order to get rid of this mode-II loading and to come back to a pure mode-I loading, as for a straight crack. Therefore, the instability will set in when this requirement of pure mode-I loading can be also satisfied by a undulating crack, besides the straight crack solution. Actually, we shall not look directly at this condition, but instead examine the relationship between the amplitude A of the undulation and the amplitude of the mode-II loading factor, denoted as K_{II}^{tot}, that is also proportional to A in the linear approximation. If the ratio K_{II}^{tot}/A is found to be positive, this means that the stress intensity factor K_{II}^{tot} and the direction of growth of the crack, as measured by $\mathrm{d}y/\mathrm{d}x$ have the same sign. According to the criterion of local symmetry, the crack tip will tend later to follow a path that decreases $|\mathrm{d}y/\mathrm{d}x|$. Therefore the amplitude of the undulation will tend to decrease later on. On the other end, if K_{II}^{tot}/A is negative, $|\mathrm{d}y/\mathrm{d}x|$ should increase to restore local mode-I loading, making the crack unstable then. So the criterion of linear instability is that K_{II}^{tot}/A should be negative.

The calculation of this ratio is not a simple matter, even in the small undulation limit. The details can be found in [1]. The final results are actually two contributions to K_{II}^{tot}/A, one with a pure geometric origin. It expresses the transformation of the mode-I loading into a mode-II loading as the crack deviates from its straight path. To leading order, for A small, this geometrical effect yields a contribution to K_{II}^{tot}/A that is given by $\omega/K_I(P,l)$, $K_I(P,l)$ being the stress intensity factor of the unperturbed case. This geometrical effect is always stabilizing, according to the criterion given before. This can be easily shown by sketching the stress distribution near crack's tip when it deviates a little bit (see Fig. 2). The other contribution to the stress intensity factor K_{II} comes from the variation of the stress field due to the crack deviation. In a certain sense, it has a geometrical origin too, as shown in Fig. 2: if one considers the stress component parallel to the x direction, it has mostly a dilation part. This dilation part, represented by two small vertical vectors for instance, once projected onto the local coordinate system of the crack yields a shear stress that is destabilizing. Clearly the onset of linear instability against undulation will be reached for the values of the parameters such that $K_{II}^{\mathrm{tot}}(P,l,\omega)$ changes sign, since the instability requires the ratio K_{II}^{tot}/A to become negative. Furthermore, since this depends also on the wavenumber ω, the marginal stability will be reached when the derivative $\partial K_{II}^{\mathrm{tot}}/\partial\omega = 0$. This yields a value $l = l_u(P)$ and $\omega = \omega_u(P)$. Typically, for values of P of order 25 to 100, that correspond to experiments, the onset of undulation is for values of the dimensionless strain $\alpha_T \Delta_T \sqrt{Eb/\Gamma}$ that are about three times bigger than the one needed for propagation of a straight crack (the dimensionless strain should be about 2 for the straight crack propagation, and 6.2 for the onset of undulation). These figures are in fair agreement with the experimental results.

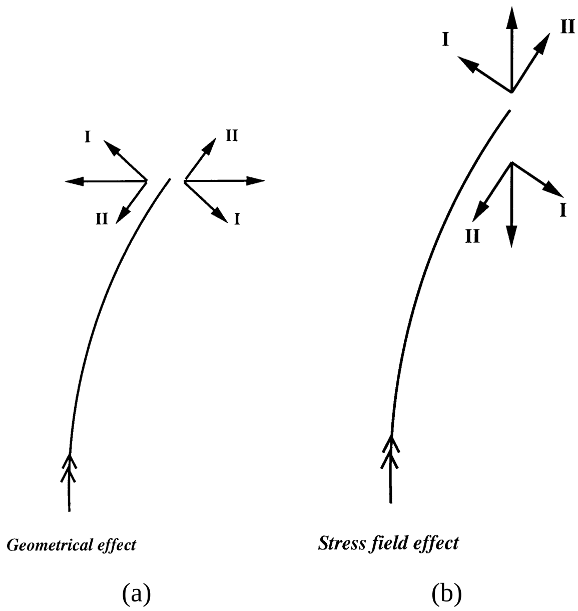

Figure 2. (a) The existing stess field is horizontal (thick arrows). When the crack tilts to the right, as shown, the local stess field keeps a mode-I opening component in the local frame of the tip, plus a new mode component that tends to bring back the crack to the vertical direction. The crack propagates upward in both Figs. 2a–b. (b) The stress has a vertical component (thick line) without influence on the vertical crack propagation. When the crack tip tilts to the right, as shown, this yields near the tip a mode-II component that is destabilizing.

3. Long time lags in breaking of stressed crystals

As alluded to in the introduction, Bercegol and Meunier [4,5] managed to crystallize monomolecular amphiphilic layers on the surface of water, and even more remarkably to visualize the long and thin crystals so produced, with a thickness in the nanometer range at most. Then they bent one of these crystals, by blocking its ends and pushing it in the middle with a glass fiber. The bending of the glass fiber measured the force exerted on the crystal. In those conditions, the crystal boundary opposed to the pushing rod is under tension (negative pressure), and so has a tendency to restore equilibrium by breaking in two pieces. I assume that the size of the crystal and the amount of stress are such that the critical Griffith crack is much smaller than the width of the crystal. Therefore, in those conditions, the crystal will break when the thermal fluctuations will trigger the formation of this critical Griffith crack. Notice that at this step, one makes already an important prediction, namely that the time needed to break is also the time required for barrier crossing by thermal activation, which means that the breaking time (i.e., the time between when the crystal was bent first and the instant of breaking) should be distributed randomly according to Poisson's law, something that has been shown not to hold in the experiments. We shall come back to this point later.

In Arrhenius like theories, the time needed to cross a barrier in configuration space is of order $\tau_\mu \exp(E_b/k_B T)$ where τ_μ is some microscopic time scale, typically in the 10^{-12} second range in condensed matter situations, although T is the absolute temperature, k_B the Boltzmann constant and E_b the free energy difference between the top of the barrier to be climbed on and the starting point. This theory is meaningful if E_b is much larger than $k_B T$. The height of the energy barrier is computed using macroscopic results, as done for instance to get the probability of homogeneous nucleation of a stable thermodynamic phase. I shall drop the constants in this calculation, although they are quite relevant, since they enter into an exponential!

Let σ be negative stress of the region of the crystal under consideration, δ be the gap between the two sides of the Griffith crack, with length $L \gg \delta$. The total elastic energy is $E(\delta/L)^2L^2$, since δ/L is the order of magnitude of the dimensionless strain, that is spread over a region of area L^2 on the crystal. Here, E is Young's modulus as usual. The marginal Griffith crack is such that its capillary energy is of the same order of magnitude as its elastic energy. The capillary energy is about $2L\Gamma$, therefore the balance of the two energies requires $E\delta^2 \approx \Gamma L$. Everything should be written now by using the value of the stress, σ, instead of the unknowns L and δ. The Hooke relation gives, in order of magnitude estimate, $\sigma \approx E\delta/L$. Putting together all those estimates, one gets that the length of the critical crack is $L \approx E\Gamma/\sigma^2$, and its free energy: $E_G \approx E\delta^2 \approx \gamma L = E\Gamma^2/\sigma^2$. This crack, once nucleated by thermal fluctuations, will be unstable against growth, and so E_G is exactly the energy barrier to be crossed by thermal fluctuations to break the crystal in two pieces. Therefore the crystal, when under bending, will break only after a time of order $t_{\text{break}} \approx \tau_\mu \exp(E_G/k_BT)$. This is an interesting result as it shows that the time before breaking grows like $\exp(\sigma_0^2/\sigma^2)$ as the imposed stress σ tends to zero, which makes a very fast growth of the stability time, so to say, as this stress tends to zero. The experimental results agree with this growth law, as well as with some other features predicted by this formula [4,5]. However there is a serious discrepancy between the predictions of this simple theory and the experiments, namely it appears that there is a memory of the bending in the breaking time: if one relaxes the bending without having reached breaking, and then bend again until breaking, the average time for breaking in this second step is shorter than without a first bending period. This is contrary to the very notion of Arrhenius process: in such a process the breaking events are randomly distributed with a Poisson distribution. In a such a Poisson process, if one restarts after relaxing the bending, everything begins from the rest state and no memory of the previous states should show-up, contrary to what is observed. This can be explained as follows: from visual observation, the crystals under study are actually made of fibers parallel to their long axis. This shows up for instance in broken crystals, when the fibers appear as tiny lines branching out of the cut, which looks like a piece of roughly cut wood. Therefore it seems natural to assume that, instead of a single Griffith crack, the thermally activated breaking process requires to cut a certain number of fibers before to become unstable against total breaking. Each 'elementary' breaking would be ruled by an Arrhenius like nucleation of a Griffith crack inside each fiber, which would not heal afterwards, even after relaxing the stress. Moreover, this explains well another observation, namely that the time before breaking fluctuate far less than what would be predicted by a single Poisson process. According to the experimentalists, one can even find the order of magnitude of the number of fibers to be broken to break the crystal itself by looking at the variance of the breaking time, and by assuming that this one is a sum of Poisson distributed times.

Similar observations have been made by the group of Ciliberto at Lyon [6], on the breaking of various heterogeneous materials, like plywood for instance. There the energy of the critical Griffith crack is like σ^{-4} instead of like σ^{-2} in two dimensions, and so the dependace o the breaking time with the stress σ is even steeper in 3D than in 2D, but still accessible to careful observations. Similarly, this group observed unrealistic values of the parameters necessary to reconcile the single step Arrhenius factor with the observations. Because of the strongly heterogeneous nature of the solid, this reflected the fact that more than one single step was involved in the breaking by homogeneous nucleation in these experiments, as in the one on the 2D crystal.

4. Summary and conclusions

This has summarized previous work on physical problems related to the breaking of solids. We emphasized that, in carefully chosen situations, it is possible to compare in a detailed fashion the theoretical predictions and the actual observations. Indeed in many situations relevant to industrial or for geophysical applications, it is sometimes difficult to apply the basic concept of crack propagation, because, among other things, of extreme heterogeneities of the materials and/or complex time dependent loading conditions. Nevertheless it is significant to know that long time scales can be due to Arrhenius factors. In an heterogeneous system, one expects that changes in the parameters in the barrier energy will become huge variations in the time scales depending exponentially of these energy barriers. Perhaps theories of the breaking of real complex materials should include too this wide range of variations of the relevant time scales for breaking. There is likely a need for bridging the gap between simple physical situations like the ones described here and the very complex situations met in industrial or geophysical applications.

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