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CLEAVAGE CRACK PROPAGATION

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ABSTRACT.

It is well known that the river patterns observed on cleavage surfaces in metals correspond to small steps on the surface created either when the cleavage crack cuts through a screw dislocation (GILMAN) or when the crack path is deflected slightly on crossing a grain boundary. The mechanism of the formation and coalescence of the river patterns has previously been analysed theoretically by one of the authors (J.F.) and the experimental verification of some of the conclusions thus derived are described and particularized in the present paper.

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The study of cleavage fracture surfaces in low-carbon steel, silicon iron and iron-chromium alloys has shown that the now well-known "tongues" (Figure 1) and "river patterns" (Figure 2) are characteristic of this type of fracture.

The tongues are due to the formation of small twins which are produced by the high stress field shead of the crack front. When the crack tip reaches one of these twins the fissure follows the interface between the twin and the parent crystal for a short distance. The conditions governing tongue formation have not been studied in detail but are probably related to the orientation of the cleavage plane, the propagation direction and the applied stress.

We shall confine ourselves in this paper to an examination of the river patterns which are created either when the cleavage crack cuts through screw dislocations or when it is deflected slightly on crossing a grain boundary (Figure 2). The mechanism of the formation and coalescence of the "rivers" has been studied theoretically by one of us (1) and some of the conclusions thus derived are verified and particularized below.

Variation of the step-height along the rivers.

a) Let us first examine the case where the rivers form and grow in the interieur of a single grain by the "drainage" from screw dislocations cutting through a given surface within the crystals. If a random distribution of screw dislocation of opposite signs pierce the cleavage plane, the height h of the step created should increase as the square root of the number of dislocations "drained". Moreover if the width of the drained zone is constant, h should increase as the square root of the propagation distance measured from the "source"(1).

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We have sought to verify this relationship by making measurements on electron-micrographs of direct-carbon replicas obtained from specimens broken by impact at liquid nitrigen temperature. Under these conditions, a significant amount of plastic deformation precedes the cleavage fracture in low carbon steel but the macroscopic deformation is negligible in iron-chromium alloys and in silicon iron. Nevertheless, in the case of silicon iron, etching with Moriss-reagent reveals a high dislocation density near the crack face.

The measurement of the heights of the river steps is not particularly easy. In certain cases, the self shadowing of the carbon film induced by a suitable arrangement of the specimen with respect to the evaporation source has been used. The height of the river step can be estimated by comparing the length of the river shadow with that of a spherical particle of known size. In general however, the measurements have been made using the width of the dark contrast zone on the micrograph corresponding to the step on the fracture surface. As shown in Figure 3, the width of this zone is proportional to the height of the step, above all when the step is propagated in a straight line. The values obtained by the two methods have been found to be in good agreement by occasional cross-checks assuming that the angle β is about 60°.

In Figure 4, several examples of the results obtained in plotting h^2 as a function of l are presented. The curves correspond to rivers on the micrographs shown in Figure 5. From the straight lines drawn through the experimental points, the density δ of the screw dislocations can be calculated after having measured the width e of the drained zone since one has :

$$h = b\sqrt{N} \quad \text{and} \quad \delta = \frac{N}{el}$$

where b is the length of the Burgers vector of the dislocations,
and N is the numbers of dislocations which have contributed to the formation of the river step of height h.

If thus follows that :

$$\delta = \frac{h^2}{b^2\, el}$$

The measurements made on 12 rivers in the metals examined here indicate a dislocation density of about 10^{12} per cm^2.(the values obtained all lie between 0.4 and 2.10^{12}). This represents a very high dislocation density which implies, if the preceeding argument is correct, that considerable local plastic deformation must be associated with the crack propagation. Such deformàtion, due to the plastic relaxation occurring at the crack front during propagation of the cleavage fissure in a ductile metal, has also been analysed (1).

It would be interesting to carry out similar experiments on very brittle materials. In the case of quartz, on which we have made a few observations, the height of the rivers are observed to be virtually constant as would be expected if the dislocation density is an order

of magnitude less than that observed in the present work.

b) In the case where the rivers are created during the crossing of a grain boundary between two crystals in which the cleavages planes are slightly disorientated (Figure 6) it is observed that in the neighbourhood of the grain boundary, the heights of the steps vary much more rapidly than in the case above. The change in height of the river step due to the intersection of the cleavage plane with screw dislocations can thus be neglected in this case and the height should then be proportionnal to the length of the drained joint. This has been verified as shown in Figure 7.

The crossing of a grain boundary by a cleavage crack.

We have seen how a cleavage crack can cross a grain boundary when the disorientation of the cleavage planes on either side of the boundary is small : a series of steps is produced which compensates for the disorientation and it appears that the cleavage fissure crosses the joint simultaneously over its entire length. The situation is rather different when the disorientation becomes important as is shown in Figures 8 and 9 which correspond to increasing disorientations. When the crack reaches the grain boundary, the propagation recommences from a limited number of points, or sometimes from a single point only (Figure 9), from which the crack fans out across the grain. The decohesion along the boundary which occurs last of all, sometimes appears as a small zone, somewhat more ductile, due to the fracture by necking-down of the residual peduncle. On the scale of our observations it appears that the points at which the crack is renucleated are situated on the boundary itself (2).

The angle at river junctions.

The angle at which the rivers join-up is determined by the energie consumed during their propagation or at least the energy consumed during the formation stage in which their position is determined. The measurement of the angle between the rivers can thus provide information concerning the mechanism of their formation.

The crack front can be considered as a cleavage dislocation, with a Burgers vector $\vec{h}$ and line tension $T = \mu h^2$, submitted to a constant applied force during propagation. The creation of a step NM resists the passage of this dislocation in a way equivalent to the application of a force $\vec{F}$ at M parallel to the direction of the river (Figure 10). This force is the origin of the confluence of the rivers (1).

If one supposes that the point M is in equilibrium and if α is the angle which NM produced makes with the tangent to the crack front at M, one has

$$2\,T\cos\alpha = F$$

Let us consider two neighbouring rivers N_1M_1 and N_2M_2 which meet at M (Figure 11) and let $P_1M_1PM_2P_2$ be an equilibriùm position of the crack front. Let $\vec{F}_1$ and $\vec{F}_2$ be the resisting forces $\vec{F}$ at M_2 and M_2.

The tangents to the arc of the circle M_1PM_2 at M_1 and M_2 each make equal an angle θ with M_1M_2. If the force applied to the crack front is constant, the radius of the circle is constant and θ approaches 0 when M_1 and M_2 approach M. The resulting configuration is represented in Figure 12 where MD is the limiting position of M_1M_2.

One has :

$$\omega = \pi - 2\alpha$$

with $\cos \alpha = F/2T$

and thus $\sin \omega/2 = F/2T$

Evaluation of F and T. Comparison with experimental results.

Several cases may be envisaged according to the ductility of the material.

a) The case of very brittle materials has already been analysed (1). Cleavage effectively occurs when a cleavage dislocation of Burgers vector $\vec{b}$ passes through the material. If T is the line tension μb^2 of this dislocation and F is the surface energy corresponding to the formation of an element of the river of height b during the displacement of the dislocation, then :

$$F = 2 b \gamma_b$$

where γ_b is the surface energy of the new surface created which may depend on the crystallographic orientation, and

$$F/2T = \gamma_b / \mu b$$

The angles ω measured on a cleavage surface of quartz lie between 15° and 60°. If the above argument applied it follows that

$$1.3 < \gamma_b / \gamma_c < 5$$

where γ_c is surface energie for cleavage and of the order of $\mu b/10$. It is réasonable for γ_b to be somewhat greater than γ_c.

b) A second case arises where the cleavage crack propagates in a completely brittle manner some distance from the river but where plastic stress relaxation can occur in the region where the step forms because of the proximity of the two crack fronts on two parallel planes. The stress diminution which occurs at the crack tip results in a diminution of the propagation velocity normal to the crack front which in turn favours stress relaxation. The limits of the lateral propagation of the two crack fronts determine the position of the step which lags behind the propagation front and it is the energy corresponding to the plastic relaxation which has to be introduced into the calculation of F. It may be supposed that the plastic relaxation which gives a radius kb/2 to the crack tip instead of b/2 is equivalent to propagation over a distance of the order of kb with a surface energy

$\gamma_{kb} = k \gamma_b$ (°).

To a good approximation,

$$F = 2 k^2 b \gamma_b$$

$$T = \mu b^2$$

and

$$\sin \frac{\omega}{2} = \frac{F}{2T} = \frac{k^2}{10} \frac{\gamma_b}{\gamma_c}$$

Since γ_b/γ_c is greater than 1, k must be greater than 3.2. Moreover the above équation implies that there is a lower limit to ω for each particular value of k. Thus if k is greater than 1.3, then ω is greater than 25°.

It is not easy to find a practical example which corresponds with certainity to this case.

c) In the metals examined in the present work, the values of ω measured on a large number of micrographs were generally found to be between 20° and 100°. We have observed also that the density of dislocations which cut the cleavage plane is always very high. There is thus a significant plastic relaxation at the crack tip.

We shall denote the radius of the crack tip by d/2. Two possibilities must be examined according to the height h of the step to be created.

1) If h is greater than 2d the position of the river is fixed by the lateral limits of the two parallel fissures due to the increase in the plastic relaxation at their tips which gives them a radius d/2. The results of the precedings section are valid on condition that b is replaced by d/2 and γ_c by $\gamma_d = \gamma_b\, d/b$; i.e.

$$F = 2 k^2 d \gamma_d$$

$$T = \mu d^2$$

$$\sin \omega/2 = F/2T = \frac{k^2}{10} \cdot \frac{\gamma_b}{\gamma_c}$$

The remarks made above concerning the values of k and ω are again valid. In view of the limits to ω observed experimentally (20° and 100°) one has

$$1.7 < k^2 \quad \gamma_b / \gamma_c < 7.6$$

(°) - When the Griffith crack condition is fulfilled $\sigma = C \sqrt{\frac{\gamma\mu}{a}}$ where a is the length of the fissure and σ the mean applied stress. The maximum stress on the crack front σ_M is equal to $C' \sigma \sqrt{a/r}$ where r is the radius of the crack tip; whence $\sigma_M = CC' \sqrt{\gamma\mu/r}$. For a fixed value of σ_M, γ/r is constant.

2) If h is less than 2d, the river is formed from the moment when each crack reaches the height h, i.e. at the propagation front itself.

$$F = 2 h \gamma_n$$

where γ_n is the surface energie of the step which is approximately equal to the surface energie of a cleavage crack whose tip is of radius h.

In addition it is necessary to take for T the line tension of the dislocations which contribute to the formation of the step, i.e.

$$T = \mu h^2.$$

Under these conditions the calculation is equivalent to that made in section (a) and replacing b by h and γ_b by γ_n

$$\sin \frac{\omega}{2} = \frac{F}{2T} = \frac{\gamma_n}{\mu h} = \frac{\gamma_b}{\mu b} = \frac{\gamma_b}{10\gamma_c}$$

For the measured values this gives

$$1.7 < \frac{\gamma_b}{\gamma_c} < 7.7$$

Preferred propagation directions.

In the case (a) the propagation of the rivers should be easier if the surface to be created corresponds to a cleavage plane i.e., in the metals we have considered, for propagation directions ⟨100⟩ . In the other cases where a certain amount of plastic deformation is possible the plastic relaxation and hence the river propagation is certainly easier if the propagation direction is parallel to a slip plane or a twin plane. In the B.C.C. system ⟨110⟩ directions, which are parallel to the {110} and {112} slip planes and to the {112} twin plane, should be the preferred propagation directions. This is often observed to be the case (Figures 5 (c) and 13). It is possible that the propagation of the rivers in the ⟨110⟩ directions occurs by a mechanism somewhat analogous to that by which tongues are formed i.e. formation of a twin followed by decohesion at the interface of the twin and the parent crystal.

For the finest rivers observed in the metals studied here, the mechanism is probably that described in paragraph (c).2. For the relatively high rivers (several hundred angstroms and above) torn zones are frequently observed (Figures 14 and 15) the dimensions of which may be 2 to 3 times the height of the rivers. The large amount of deformation in these zones should correspond to a very high surface energy. Such zones are probably formed a good way behing the crack front as indicated schematically in Figure 16. Their position is probably determined, as the crack front passes, by the interaction of the two fissures on parallel planes by the mechanism of section (c).1.

References.

(1) - J. FRIEDEL. - Fracture (Swampscott Conference), Wiley (1959), p. 498.

(2) J. PLATEAU, G. HENRY and C. CRUSSARD. - Rev. Mét. (1957), 54, 200.

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Figure 1 - Low carbon steel. Impact cleavage fracture at - 196°C. "Tongues".

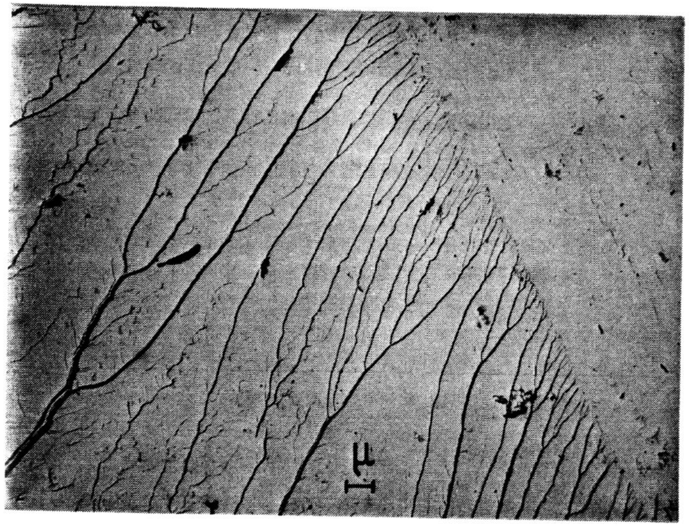


Figure 2 - Iron-chromium alloy. Impact cleavage fracture at - 196°C. "River patterns".

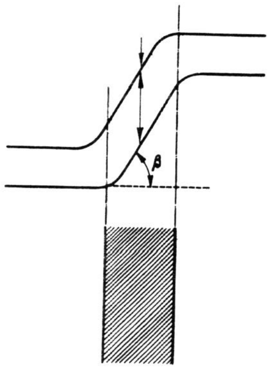


Figure 3 - Schematic representation of "river" contrast on direct carbon replica. Above, section through carbon film. Below, contrast observed on the electron-micrograph.

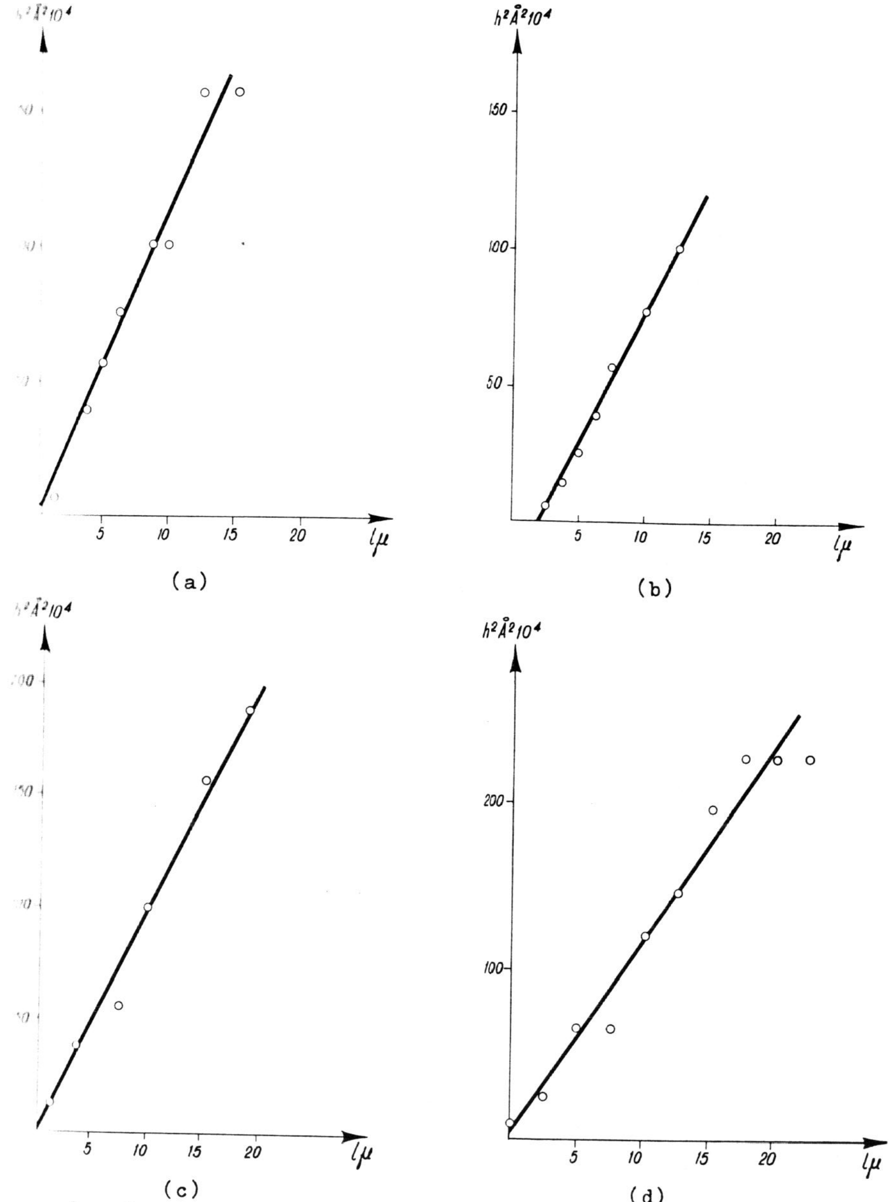


Figure 4 - Variation of the square of the step height h as a fonction of the distance l along the river.
(a), (b), (c) - mild steel.
(d) - iron-chromium alloy.

Figure 5 - Microfractographs of the rivers whose heights are plotted in figure 4.
A - curves (a) and (b) - mild steel
B - curve (c) - mild steel.
C - curve (d) - iron-chromium alloy.

Figure 6 - Cleavage in Armco iron. Crossing of grain boundary between two grains in which the respective cleavage planes are slightly disoriented. The crack propagation is from the top towards the bottom of the micrograph.

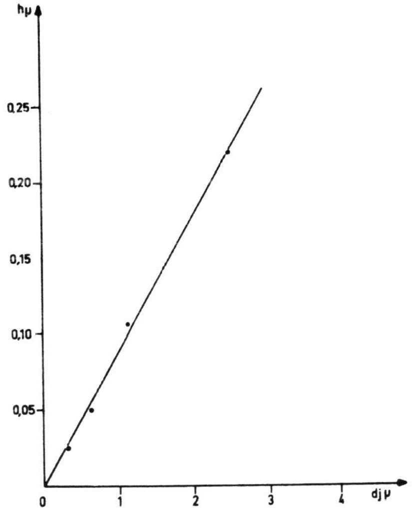


Figure 7 - Variation in the height of a river step, during the crossing of a grain boundary, as a function of the length dj of the "drained" grain boundary. Low carbon steel broken at - 196°C.

Figure 8 - Low-carbon steel. Crossing of grain boundary : renucleation of crack at several different points. The direction of crack propagation is from the upper right towards the lower left corner of the micrograph.

Figure 9 - Low-carbon steel. Crossing of grain boundary; renucleation of crack at a single point from which the crack fans out across the grain.

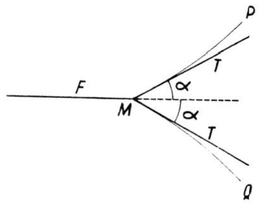


Figure 10 - Schematic representation of the forces acting during the formation of a river step.

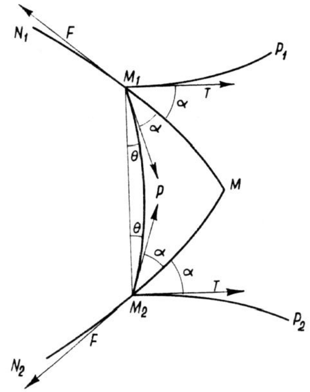


Figure 11 - Schematic representation of the forces acting during the formation of two rivers which eventually meet at the point M.

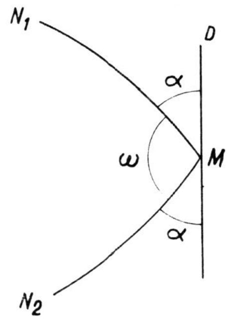
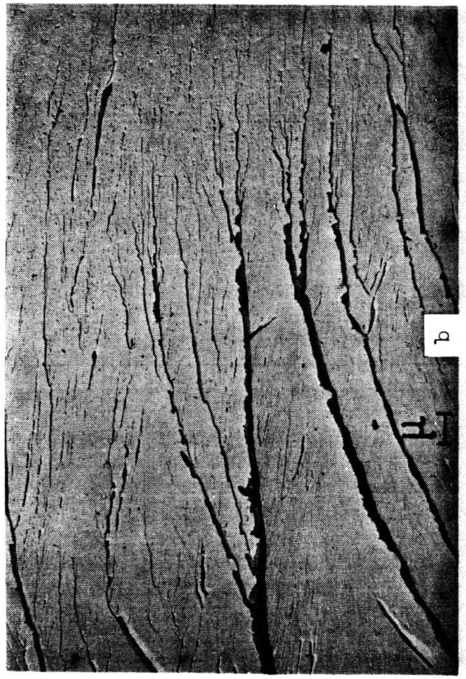


Figure 12 - Schematic representation of the configuration at the junction of two rivers at M.



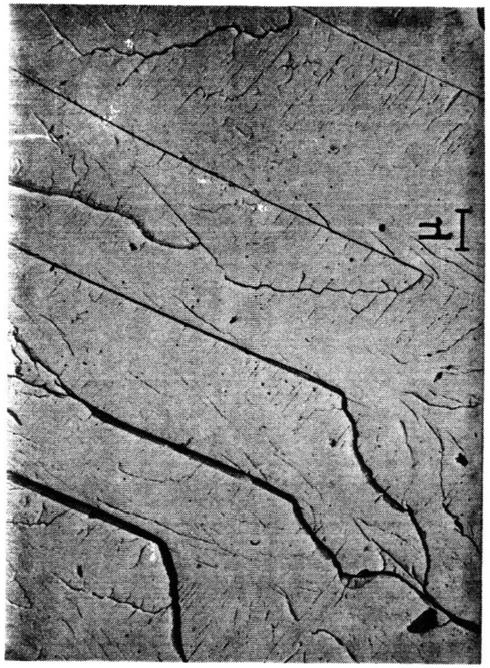


Figure 13 - Cleavage in an iron-chromium alloy, showing preferential propagation of the rivers along ❮110❯ directions.

Figure 14 -

Cleavages in low carbon steel. The rivers correspond to very high steps produced by "tearing".

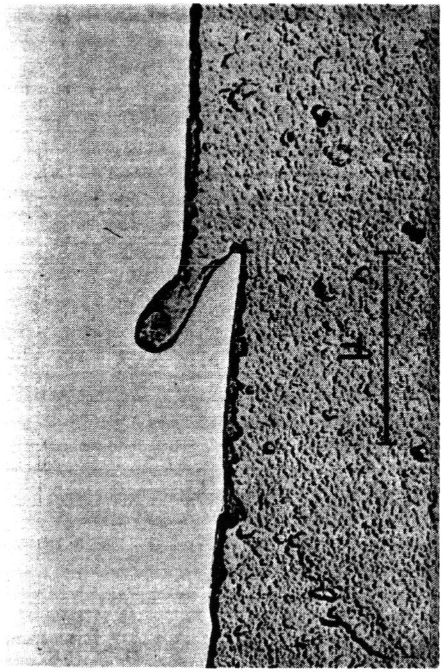


Figure 15 - Electron-micrograph of cleavage crack profile in a silicon-iron, showing zones in which "tearing" has occurred along the rivers.

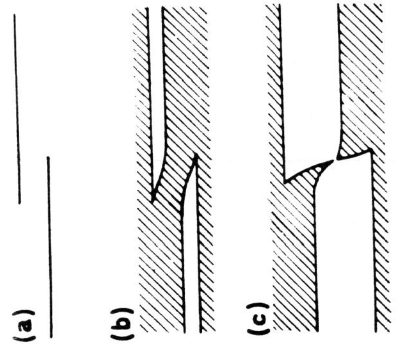


Figure 16 - Schematic representation of the river step formation by the mechanism described in section 1.C.
(a) (b) (c) represent successive sections through the step, normal to the direction of propagation, at increasing distances from the crack front.