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ON CRACK PROPAGATION ALONG CRYSTALLOGRAPHIC SLIP BANDS

By

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ON CRACK PROPAGATION ALONG CRYSTALLOGRAPHIC SLIP BANDS

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Abstract

The influence of the crystallography of slip (fcc, hcp, and bcc) on crack propagation along planar slip bands is examined for two different mixed-mode crack configurations. If a crack propagates along a slip band and the Burger's vector of slip within that band is contained in the plane of the crack (i.e., coplanar slip), then non-coplanar slip is hindered and large normal stresses develop near the crack-tip. The magnitude of these normal stresses is largest for basal plane cracking in a hcp material. However, the calculations show that the magnitude of the plastic constraint factor is also large for an inclined crack in fcc and bcc alloys fracturing along crystallographic slip bands with the resulting normal stresses being comparable to a mode I crack in a polycrystalline material. Thus, cracking along crystallographic slip bands is characterized by a combination of intense coplanar slip and large normal stresses. Easy crack propagation across individual grains and a susceptibility to hydrogen embrittlement may result as a consequence.

Introduction

The propagation of a crack along a crystallographic slip band is a common occurrence in high strength alloys. Such crystallographic cracking is ductile in nature and occurs on an extensive scale in materials susceptible to planar, non-uniform slip, such as high strength Ni-, Al-, and Ti- base alloys. One of the features of fracture along crystallographic slip bands is that even though the crack path occurs along planes experiencing large shear stresses, the resulting fracture surface is usually characterized by a substantially brittle or cleavage-like appearance. This suggests that normal stresses as well as shear strains are important in this fracture process.

Koss & Chan (K & C) have very recently examined certain conditions for the propagation of a crack along a coplanar slip band (1). In their analysis of the crack-tip plastic zone, the plastic displacement is restricted to a shear parallel to the crack plane and such crack/slip interaction results in a relaxed "elastic-plastic" state of stress near the crack tip. Calculations by K & C indicate that once a crack with a coplanar slip band has formed, it becomes difficult to activate secondary slip with a Burger's vector inclined to the crack plane. As a result, large normal stresses can be generated near the crack-tip. The purpose of this paper is to explore certain implications of crack propagation along planar slip bands with regard to the crystallography of slip in fcc, hcp, and bcc alloys. Such cracking is always observed under combined tensile and shear loading, and thus the influence of crack orientation as regards the importance of mode II (in-plane shear) vs. mode III (anti-plane shear) mixed with the normal mode I opening will also be explored.

Crack Propagation Along Planar Slip Bands

The basis for understanding crack propagation along a coplanar slip band is contained in Fig. 1 and is discussed in more detail by K & C (1). The singularity in the elastic stress field near the tip of a mixed mode crack dictates that if r is the radial distance from the crack-tip, then $\sigma_{ij} \propto 1/\sqrt{r}$, where σ_{ij} is a stress component. Sufficiently close to the crack-tip, the stresses may be described by the tensor $\overset{\leftrightarrow}{\sigma}$ which activates slip with a critical resolved shear stress τ_y, whose normal in $\hat{n}$ and with a Burger's vector $\vec{b}$ when:

$$\tau_y = \left(\frac{1}{b}\right) \vec{b}\cdot\overset{\leftrightarrow}{\sigma}\cdot\vec{n} \tag{1}$$

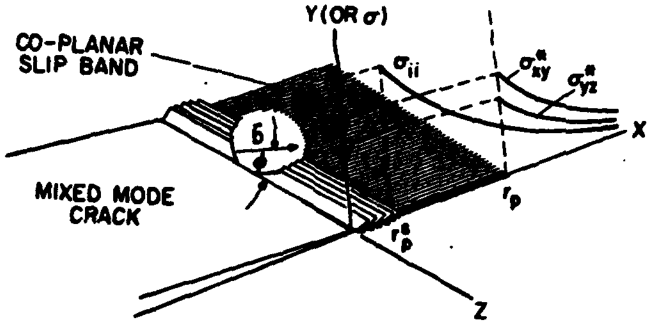


Fig. 1. A schematic illustration of the stress state ahead of a mixed mode crack with a coplanar slip band characterized by a slip vector $\vec{b}$ at an angle ϕ to the crack front. The coplanar slip extends to r_p while secondary slip is activated to r_p^s (after Koss and Chan, ref. 1).

Through the inverse square root dependence of the stress components on r, Eq. (1) can be used to estimate (ignoring plastic relaxation (2), crack-tip blunting, and work hardening) the plastic zone size r_p. For a material characterized by multiple, non-coplanar slip at the crack-tip (as is typical of a mode I crack), r_p indicates roughly the position at which all stress components are plastically relaxed. In contrast, if crack-tip plasticity is dominated by planar slip whose Burger's vector is also coplanar with the crack, then at r_p Eq. (1) is:

$$\tau_y = \sigma_{xy}^* \sin\phi + \sigma_{yz}^* \cos\phi, \tag{2}$$

and only the shear stresses σ_{xy} and σ_{yz} are plastically relaxed to values of σ_{xy}^* and σ_{yz}^*. At the same time, the normal stress components σ_{ii} continue to increase at $r < r_p$ in an elastic manner until a stress state is reached at $r = r_p^s$ at which slip with a non-coplanar Burger's vector is activated. This "relaxed" elastic-plastic stress state is schematically shown in Fig. 1. The stress tensor which activates non-coplanar slip in the plane of the crack thus is:

$$\overset{\leftrightarrow}{\sigma} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy}^* & 0 \\ \sigma_{xy}^* & \sigma_{yy} & \sigma_{yz}^* \\ 0 & \sigma_{yz}^* & \sigma_{zz} \end{bmatrix} \tag{3}$$

Eq. (3) shows that the increase in shear stress necessary to activate non-coplanar slip at $r = r_p^s$ according to Eq. (1) must arise from the normal stress components. In plane strain this stress state is obviously not conducive for the activation of secondary slip but is well suited for the development of large hydrostatic stress. Thus, once a crack begins to propagate along a coplanar slip band, it becomes difficult to activate non-coplanar slip which in turn generates large normal stresses near the crack-tip. This is shown schematically in Fig. 2. The combination of the large normal stresses and the intense coplanar slip should result in relatively easy crack propagation along the coplanar slip bands and in crack surfaces which, reflecting the large normal stresses, may have a cleavage-like or substantially brittle fracture appearance. This has been observed in a number of Al-, Ni-, and Ti- base alloys.

Application to Fcc, Hcp, and Bcc Alloys

Crack propagation along crystallographic slip bands is usually observed in single crystals, individual colonies or large grains of high strength alloys. As such, the crystallography of slip should have a significant influence on the ability of a given material to activate non-coplanar slip and therefore on the

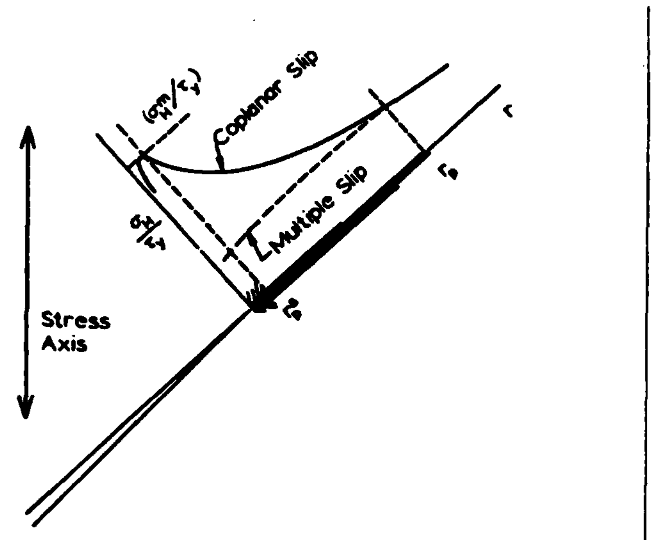


Fig. 2. The approximate distribution of the hydrostatic stress/yield stress ratio ahead of a mixed mode crack exhibiting either coplanar or multiple slip.

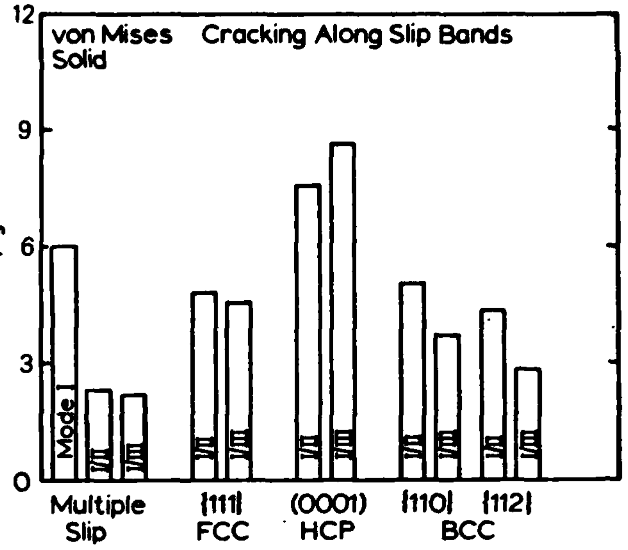
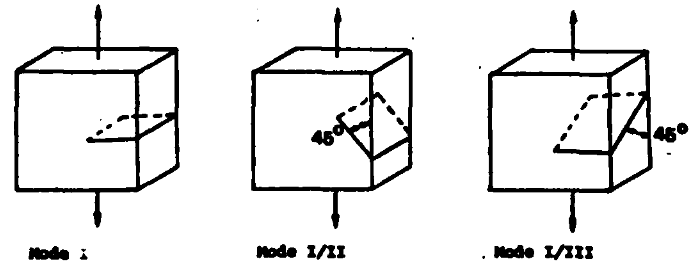


Fig. 3. A comparison of the approximate values of the maximum principal stress/yield stress ratios for cracks characterized either by multiple slip or coplanar slip in selected crystal systems. The crack geometries (i.e., mode I, I/II, or I/III) are defined in Table I.

Table I. A comparison of the magnitude of the approximate maximum normal stresses near the tip of cracks with differing orientations and with differing crack-tip slip behavior.

	Cracking/Multiple Slip			Crack Propagation Along Crystallographic Slip Bands							
Constraint	von Mises Solid*			Fcc Crystal		Hcp Crystal		Bcc Crystal Crack {110}-crack plane-{112}			
Factor⁺	Mode I	I/II	I/III	I/II	I/III	I/II	I/III	I/II	I/III	I/II	I/III
				(111) [$\bar{1}$01]**		(0001) [11$\bar{2}$0]**		(011) [$\bar{1}$1$\bar{1}$]**		(211) [1$\bar{1}\bar{1}$]**	
σ_H^m/τ_y	5.3	1.0	1.0	3.3	3.3	5.9	7.3	3.5	2.8	3.1	1.9
σ_1^m/τ_y	6.0	2.3 [~6, continuum plasticity (3)]	2.1	4.7	4.2	7.6	8.6	5.0	3.7	4.5	2.8
σ_{yy}^m/τ_y	6.0	1.1	1.1	3.7	3.7	6.6	8.2	4.0	3.1	3.5	2.1
Secondary Deformation Systems:				($\bar{1}$11) [101]	($\bar{1}$11) [110]	twins (10$\bar{1}$2) [$\bar{1}$101]	($\bar{1}$012) [10$\bar{1}$1]	(12$\bar{1}$) [$\bar{1}$11]	($\bar{1}$2$\bar{1}$) [111]	(21$\bar{1}$) [$\bar{1}$11] (2$\bar{1}$1) [11$\bar{1}$]	(2$\bar{1}\bar{1}$) [111]
Crack Orientations:											

⁺ Values are calculated by assigning $r = r_p$ (von Mises) or $r = r_p^s$ (single crystal) in the following relations: $\sigma_H^m = \frac{4}{9}\sigma\sqrt{\frac{a}{2r}}$, $\sigma_{yy}^m = \frac{\sigma}{2}\sqrt{\frac{a}{2r}}$, and σ_1^m is from the solution of: $\sigma^3 - \frac{8}{3}\lambda\sigma^2 + (\frac{7}{3} - \frac{r_p^s}{r_p})\lambda^2\sigma + (\frac{2}{3}\frac{r_p^s}{r_p} - \frac{2}{3})\lambda^3 = 0$, where $\lambda = \frac{\sigma}{2}\sqrt{\frac{a}{2r_p^s}}$.

* Assuming $\sigma_y = 2\tau_y$

** Denotes y and x axes for mode I/II crack and y and z axes for mode I/III crack.

magnitude of normal stresses near the crack-tip. Crack propagation along crystallographic slip bands also occurs on planes inclined to the stress axis such that the mode I crack opening component is mixed with the mode II and/or mode III shear components.

Table I and Fig. 3 shows the influence of slip crystallography for fcc, hcp, and bcc deformation systems. These normal stresses have been calculated using Eqs. (1-3) and should be reasonable estimates; most of the details to such calculations are described in the appendix of the K & C paper.+ This procedure is based conceptually on Figs. 1 & 2 and as such, the normal stresses are determined by Irwin's elastic stress intensity factor at either $r = r_p$ (multiple slip) or $r = r_p^s$ (coplanar slip). While crude, this method none-theless yields a value of σ_1^m for a mode I crack which agrees well with continuum plasticity estimates (3) as is shown in Table I. A principal difference in the two methods is that the present approach would place σ_1^m much nearer the crack-tip (3). Finally, it should be noted that these calculations assume isotropic elasticity, which is a very good assumption for materials with an anisotropy ratio of less than 2.

As shown in Table I and in Fig. 3, there are relatively large normal stresses near the tip of a mode I crack with multiple slip obeying a von Mises yield criterion at the crack-tip. However, there is a large decrease in normal stresses for a von Mises material when crack becomes inclined to the stress axis (for example, compare σ_H^m/σ_y or σ_1^m/σ_y for mode I vs. modes I/II or I/III). This is a principal reason why cracks initially inclined to the stress axis generally deflect into a mode I configuration upon subsequent propagation in a polycrystalline material. In contrast, crack propagation along inclined, coplanar, crystallographic slip bands is characterized by normal stresses which are much larger than inclined, "multiple" slip cracks. In fact, taken as a whole, σ_1^m, σ_H^m, and σ_{yy}^m as shown in Table I generally compared favorably in magnitude with that of a mode I crack. Thus it should not be a surprise that such cracks appear relatively content to continue propagating along crystallographic slip planes until microstructural features (i.e., grain boundaries, interphase boundaries, etc.) cause arrest or deflection or branching.

An interesting feature of the results in Table I and Fig. 3 is that, despite many secondary slip systems, large normal stresses can be generated by crystallographic slip band cracking in both fcc and bcc crystals. An implication of this behavior is that a cubic alloy which is otherwise immune to hydrogen embrittlement may become sensitive to hydrogen if heat treated so that planar slip and coplanar cracking occurs. This in fact has been observed in the case of age hardenable β Ti alloy tested in fatigue in a hydrogen environment (4).

As expected, very large normal stresses should be present near the tip of a crack propagating along a coplanar slip band in an hcp crystal. This is due to the difficulty of activating slip or twinning which causes an extension (or relaxation of the normal stresses) in the C direction, normal to the (0001). Twinning on the $\{10\bar{1}2\}$ $<\bar{1}101>$ system is very common to most hcp alloys and should be activated near the crack-tip to relieve the normal stresses. Observations of Stage I, basal cracking in α and α-β Ti alloys show that $\{10\bar{1}2\}$ twins are indeed found near the tip of crystallographic cracks (5).

As shown in Table I, the influence of the crack orientation is such that the plastic constraint factors for mode I/II cracks are similar to those of a mode I/III crack for fcc and hcp material. This is surprising since there is not a larger difference since a mode II crack generates normal stresses while a mode III crack does not (assuming isotropic elasticity). All of the cases

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+In the K & C paper (1), there is an error in the calculation of σ_1^m, which is used to demonstrate the model. The correct value, as indicated in Table I, should be $\sigma_1^m = 2.3\ \sigma_y$ for Fig. 2a and $\sigma_1^m = 2.0\ \sigma_y$ for Fig. 2b.

examined in Table I refer to cracks inclined to the stress axis at 45°. Calculations show that a more inclined crack (mode I component becomes smaller) has a smaller r_p^s and therefore the normal stresses at the crack-tip exceed those in Fig. 3.

Acknowledgments

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References

1. D. A. Koss and K. S. Chan, Acta. Met. (in print).
2. G. R. Irwin, Proc. 7th Sagamore Conf., p. IV-63 (1960).
3. J. R. Rice in *Stress Corrosion Cracking and Hydrogen Embrittlement of Iron Base Alloys*, p. 11, NACE, Houston, 1977.
4. J. R. Wilcox and D. A. Koss, to be published in the Proc. to the *3rd Int. Conf. on the Effect of Hydrogen on the Behavior of Metals*, Jackson Hole, Wyoming (1980).
5. K. S. Chan and D. A. Koss, Mat'l. Sci. and Eng. *43*, 177 (1980), also C. C. Wocjik and D. A. Koss, unpublished results.

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cracking in a hcp material. However, the calculations show that the magnitude of the plastic constraint factor even for an inclined crack in fcc and bcc alloys fracturing along crystallographic slip bands is also large and comparable to a mode I crack in a polycrystalline material. The combination of the intense shear caused by the planar slip and the large normal stresses should result in easy crack propagation across individual grains and could result in a susceptibility to hydrogen embrittlement.