SIMULATION OF VOID — CRACK INTERACTION BY A
FINITE ELEMENT FRACTURE MECHANICS TECHNIQUE*

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SUMMARY

Most commonly employed metals are polycrystalline and, as such, are neither homogeneous nor isotropic at the sub-macroscopic level. In an earlier paper, Hartz and Chopra presented a technique for investigation of multiple fracture of such a material. This work is now expanded in an attempt to analytically treat different secondary crack or imperfection configurations and interpret these configurations in terms of actually occurring metallurgical phenomena. The latter include grain boundaries, dislocations (loops, lines, and networks) and large porosity. Further refinement of this technique is expected to provide a method for analyzing secondary cracks represented by sub-microscopic inhomogeneities such as the voids formed in stainless steel during fast neutron irradiation.

The basic analytical tool is a generalization of the Griffith criteria via the Hartz function. This tool incorporates not only the influence of non-homogeneous and anisotropic materials and of multiple fractures on the stress distributions and strain energy release rates, but also the differences in surface energies for forming new fracture surface such as exist when fracture surfaces follow grain boundaries in crystalline materials or boundaries of inclusions as in the case of concrete.

Results are presented for several cases of initiating and incrementing secondary imperfections at various locations and orientations relative to a main fracture. These results are compared qualitatively with results of experimental observations obtained from the literature.

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1. Introduction

Structural materials used in neutron environments are known to develop voids along grain boundaries as well as in the matrix [1-4]. Examples of these voids are shown in Figs. 1 and 2. Such voids enhance the degree of inherent anisotropy and polycrystallinity of these materials. A major concern of designers of reactor core structures is the fracture resistance of irradiated materials which demonstrate significantly reduced ductility in post-irradiation tensile tests and reduced creep and fatigue strengths [5,6]. Some insight into the reduced fracture resistance of irradiated materials may be obtained with the help of the generalized energy rate fracture hypothesis proposed by Hartz and Chopra [7].

The present study investigates the interaction between a primary crack in a material containing a variety of parallel, orthogonal and inclined flaws. In this presentation it is assumed that void lattices can be simulated by linear flaws with specific surface energies ranging from zero to that of the matrix.

2. Analytical Approach

The generalized energy rate fracture hypothesis, has been described previously [7] and is summarized here. The Hartz function, \( H(a) \) is given by:

\[
H(a) = G_T(a) - K_I(a) > 0
\]

(1)

where \( G_T(a) \) is the instantaneous total strain energy release rate for crack formation as a function of the fracture incremental area, \( \Delta a \); and \( K_I(a) \) is the instantaneous rate of conversion of available energy into the energy required for crack formation.

The strain energy release rates, \( G_T(a) \) can be obtained from finite element solutions of successive boundary value problems, corresponding to progressive fracture configurations, which yield the total strain energy stored in the body as described earlier [7].

The fracture hypothesis states that in an elastic solid body experiencing fracture under the action of specified surface tractions, the relative locations, size and orientation of crack initiation and propagation configurations are determined by the corresponding values of the Hartz function, \( H \).

In the present investigation, the strain energy stored in the structure is assumed to be independent of the presence of voids. This is the same as assuming that the collective effect of voids is reflected in a average "effective" value of the elastic constants \( E \) and \( v \). However, a series of voids may form a secondary crack or flaw. Such a flaw is suggested by Figs. 3 and 4 in which a "wall" of voids, which is thought to be three dimensional, and a regular array of voids, or void lattice, may be seen. The change in the strain energy of the structure due to the presence of such formed flaws is considered.

The physical model selected is an edge cracked panel under uniaxial tension shown in Fig. 5. The primary crack length varied from 0.2" to 0.3" and the lengths of the secondary flaws (or defected void lattices) varied from 0.025" to 0.15". Further refinement of the flaw sizes would be desirable for a more representative simulation of irradiation-induced voids. However, such a refinement is not expected to modify the results materially.
The secondary flaw length to primary crack length ratio of 0.1 to 0.5 does not change significantly in scaling down to a fuel element cladding-type structure. For these it is believed that primary cracks exist down to lengths of 0.001-0.002". Arrays of voids, both in the matrix and along grain boundaries, result in secondary flaws of the order of 0.0001" or 0.05 to 0.10 of the primary crack length.

The material parameter, $R_p$, is not determined in this investigation. It is assumed however that the ratio of the resistance along secondary flaws of ordered porosity to that of the matrix or parent material, $R_{TP}/R_{TP}$ ranges from 0 to 1. The study examines the relative values of $G_{n}$ for primary crack propagation through the matrix, $G_{TP}$, and those for the initiation or propagation of flaws along predefined lines. Such lines often may be predefined by the grain boundaries along which voids may be present in higher concentrations, e.g., Fig. 1.

A shortcoming of the present application is the use of a two-dimensional finite element description of the structure. This assumes that the primary crack and the flaws extend throughout the thickness of the plate. This shortcoming can be removed with the use of a three dimensional finite element code in which flaws may be assigned desired depths and locations along the thickness direction.

2. Results

Selected results are presented to demonstrate the interaction between a primary crack and orthogonal, parallel and inclined flaws.

2.1 Parallel Flaws

Figure 6 shows the variation in $G_{TS}$ for opening symmetrical parallel secondary flaws as a function of their separation distance, $X$. $G_{TS}$ is maximum at approximately $X = .1$ with value of $2.5^{1} \#/$in. compared with $G_{TP} = 69.5 \#/$in. for primary crack propagation. This suggests that a ratio of $R_{p}/R_{TP}$ less than approximately 1/28 will be required for opening the flaw in preference to continued propagation of the primary crack.

For longer primary crack tip approaches the location of the secondary flaws (measured by the parameter $Y$) the maximum value of $G_{TS}$, $G_{TM}$, increases and the flaw distance, $X_m$, at which this maximum value occurs also decreases. This is demonstrated by curve ABC in Fig. 7 which gives the value of $G_{TM}$ and curve ABC which gives the corresponding value of $X_m$. As the crack tip crosses the flaw location and the parameter $Y$ assumes a negative value, the value of $G_{TM}$ drops more rapidly than for positive values of $Y$ and the distance $X_m$ increases at a more rapid rate. This is demonstrated by curves CDE and CDE in Fig. 7.

From Fig. 7 it appears that symmetrical parallel cracks are most likely to initiate at flawed locations adjacent to a primary crack. The separation distance between the secondary cracks for the most likely initiation case tends to zero. Advance parallel secondary cracking is more likely to occur than posterior cracking.

Figure 7 also shows the ratio of $G_{TM}$ to $G_{TP}$ expressed in terms of $\bar{G}$. This ratio, $\bar{G}$, approaches .125 as $Y$ tends to zero. This suggests that $R_{TS}$ should be less than .125 $R_{TP}$ to initiate advance parallel secondary flaws.

\[1\] In the interest of simplicity, a constant factor in the units is dropped.
The effect of primary crack length on $G_{TS}$ for opening a collinear flaw immediately ahead of the crack tip, is shown in Fig. 8. The total strain energy release rate for advance secondary crack formation is higher for longer primary crack lengths. In addition, the ratio $G_{TS}/G_{TP}$ also increases with the primary crack length.

Several investigators [8,9,10] either have observed or conjectured the formation of advance parallel secondary cracks. The results of Fig. 7 can be used to explain this phenomenon, with the help of the function $N$, in polycrystalline materials and in some irradiated materials. It is reasonable to assume that material flaws are present and the specific surface energy, which determines the value of $R_{P}$, is not constant throughout the material. The general criterion for rupture is given by $N = G_{T} - R_{P} > 0$. The function $N$ therefore, will not vary directly with $G_{T}$ alone, but with the difference between $G_{T}$ and $R_{P}$. In Fig. 7, $G_{TM}$ = 9.9 $\#$/in. for $Y = 0$ and 4.0 $\#$/in. for $Y = 0.5$. Suppose now that material flaws are present at the maximized positions $X_{m}$ corresponding to $Y = 0.5$. Suppose also that the intrinsic value of $R_{P}$ for the material is greater than 9.9 $\#$/in., under the given loading and environment, and the value of $R_{P}$ associated with the flaws is less than 4.1 $\#$/in. For these conditions, a value of $N > 0$ will be realized for advance secondary flaw opening indicating that advance cracking should be possible.

2.2 Orthogonal Flaws

Parametric studies of the total strain energy release rates for symmetrical orthogonal secondary flaw opening, are presented in Figs. 9 and 10. The first of these figures shows the variation of $G_{TS}$ as a function of the separation distance, $Y$, for a primary crack of length 0.3". The value of $G_{TS}$ is maximum for $Y = 0$. The discontinuity in the plot at this point, is caused by a sudden increase in the value of $G_{T}$. This occurs when the primary crack connects with an open secondary flaw, thereby causing a large increase in the strain energy stored in the panel without any appreciable change in the cracked surface area. At $Y = (0 + \Delta Y)_{AY-O}$, ahead of the primary crack tip, the value of $G_{TS}$ for secondary flaw opening is 14.2 $\#$/in. Immediately after the crack connects with the open flaw, for $Y = 0$, the value of $G_{TS}$ is 35.3 $\#$/in.

The increase in $G_{T}$ without an appreciable change in $R_{P}$, due to the connection of a crack with open flaws results in a sudden increase in $N$. This instantaneous increase in $N$ makes excess energy available for acceleration of the fracture process. Only part of this excess energy is utilized for accelerating the crack tip. Some of the excess energy may produce thermal and acoustical waves. This is evidenced by the sharp noises sometimes emitted during brittle fractures. These noises may be precipitated by the connection of several micro-cracks with one another or with the primary crack. This also may explain the surface roughness generally associated with noisy, rapidly running fractures.

A comparison of $G_{TS}$ for advance and posterior orthogonal secondary flaw opening, also is given in Figs. 9 and 10. In Fig. 10, ratios of $G_{TS}$ to $G_{TP}$ also are shown. The values of $G_{TS}$ and $G_{TS}/G_{TP}$ drop off more rapidly for $Y < 0$ than for $Y > 0$, as in the case of parallel secondary flaws.

Figure 10, drawn for a variable primary crack length, shows the same general trends as observed in Fig. 9. From these two figures, it is seen that discontinuities are present in the fracture process during crack intersection. The value of $G_{TS}$ for
orthogonal secondary flaw opening, is maximized for secondary flaws which open at the tip of the primary crack. The values of $G_{TS}$ are greater for advance rather than posterior flaw opening. Furthermore, a comparison of the two figures shows an increase in the maximum value of $G_{TM}$ from 24.4 $\#$/in. for a primary crack length of .25", to 35.5 $\#$/in. for a primary crack length of .3". In addition, the ratio $G_{TS}$/$G_{TP}$ for the same value of $Y$ is higher for the longer primary crack. These results indicate a greater likelihood of orthogonal secondary flaw opening with increasing primary crack length for the case of constant stress boundary conditions.

Beacham, et al. [10], demonstrated recently by examining fracture surfaces ahead of interrupted cracks that orthogonal secondary cracks nucleate in front of the crack tip in low alloy steels. This experimental evidence supports the analytical predictions, made by Figs. 9 and 10, of advanced orthogonal secondary flaw opening. It is expected that ordered porosity in irradiated materials would demonstrate a similar fracture pattern.

A case of crack arrest by an open orthogonal secondary flaw in studied in Fig. 11. Values of the total strain energy release rates are shown as a function of the flaw length, for primary crack propagation, as well as for propagation of the flaw. $G_{TS}$ for flaw propagation appears to be relatively insensitive to the secondary flaw length. However, there is a strong influence of the flaw length upon the continued propagation of the primary crack. This is indicated by the sharp decline in the value of $G_{TP}$ with increasing flaw length. The values of $G_{TS}$ are greater than $G_{TP}$ for flaw length ratios, $a_s/a_p$, greater than approximately .22 in Fig. 11, indicating that $G_{TS}$ for longer orthogonal flaws propagating in an orthogonal direction can exceed $G_{TP}$ for primary crack propagation.

2.3 Inclined Flaws

When a primary crack tip approaches a grain boundary or a material defect at an angle of incidence defined in terms of the grain or flaw shape parameter, $\theta$, its interaction with the flaw also was studied.

The influence of flaw shape on the total strain energy release rate for opening a branch flaw, $C_{TB}$, is shown in Fig. 12. The flaw shape parameter, $\theta$, is defined as the angle measured from the primary crack axis to either branch of a symmetrical flaw. The flaw corresponding to $\theta = 0$ represents the path of a propagating primary crack. In Fig. 12, the value of $G_{TB}$ is maximum for $\theta = 0$ and the value of $G_{TB}$ decreases with increasing values of $\theta$. This indicates that "forking" flaws, corresponding to lower values of the flaw shape parameter $\theta$, are more likely to cause crack branching than "arrowhead" flaws.

For the case of forking flaws at an angle, $\theta = 45^\circ$, $C_{TB}$ for opening one branch of the flaw was found to be 1.6 times greater than $C_{TB}$ for opening both flaws simultaneously. This suggests that fracture patterns are more likely to be non-symmetrical even in materials which contain symmetrical flaws. An example of non-symmetrical fracture propagation in an irradiated EBR-II fuel element cladding is shown in Fig. 13.

A study of primary crack arrest by branching towards open symmetrical parallel flaws, is shown in Fig. 14. Values of the total strain energy release rates are shown as a function of the flaw lengths for two propagation configurations. In the first configuration, the primary crack branches and connects with the flaws. The values of $G_{TS}$ for this
case increase steadily with flaw length. The second configuration represents the primary crack propagating along its axis. Values of $C_{TP}$ for this appear to be relatively insensitive to flaw length. A comparison of the two curves, for the cases studied, shows that $C_T$ is higher for crack branching than for primary crack propagation. This comparison is accentuated by the plot of the ratio $C_{TS}/C_{TP}$ versus secondary flaw length. This ratio is greater than unity for the cases studied and increases with the lengths of the flaws. These results indicate that the primary crack will branch and connect with the flaws. In addition, the tendency for the crack to branch increases with the flaw length. An explanation for this behavior is obtained by considering the stress shadowing of the material between the two open flaws and ahead of the primary crack tip.

3. Conclusions

A simplified fracture model based upon the strain energy release rate has been proposed for investigating the interaction between cracks and voids. The model yields results which are in general agreement with fracture observations in materials with flaws. If it is hypothesized that radiation-induced voids, arranged in ordered forms resembling material flaws, result in fracture behavior similar to conventional flaws, the model may be applicable to the investigation of fracture in irradiated materials such as that shown in Fig. 15 [11]. Refinement of the physical finite-element model of the structure and experimental verification of the hypothesis are necessary before this technique may be employed quantitatively.

References

Fig. 1. Enhanced Void Development Near Grain Boundaries at $1.6 \times 10^{22}$ Neutrons/cm$^2$ (E>0.1 MeV). (a) 8001 Alloy at 55°C. (b) High Purity Aluminum at 150°C Ref. [1].

Fig. 2. Voids in Type 316 Stainless Steel Fuel Element Cladding Irradiated to $7.1 \times 10^{22}$ Neutrons/cm$^2$ (E>0.1 MeV) at 525°C. Mean Void Diameter, $2.5 \times 10^{-6}$ Inch;Void Density, $4.4 \times 10^{14}$ Voids/cm$^3$; Swelling 8.7% AV/V Ref. [2].
Fig. 3. Wall of voids formed in high-purity aluminum irradiated to $5.2 \times 10^{20}$ neutrons/cm$^2$ ($E > 0.1$ MeV) at 550$^\circ$C. Wall is thought to mark the position of a prior grain boundary which was swept away during recrystallization but left void-nucleating defect clusters behind Ref. [3].

Fig. 4. Three-dimensional void ordering in molybdenum irradiated to $2.5 \times 10^{22}$ neutrons/cm$^2$ ($E > 0.1$ MeV) at 585$^\circ$C Ref. [4].
Fig. 5. Description of Fracture Configurations Containing Primary Crack and Secondary Flaws.

Fig. 6. Total Strain Energy Release Rate, $G_{TS}$, for Opening Parallel Flaws as a Function of their Separation Distance.

Fig. 7. Relative Positions of Primary Crack and Parallel Flaws to Maximize the Total Strain Energy Release Rate, $G_{TM}$, for Secondary Crack Formation.

Fig. 8. Effect of Primary Crack Length on the Total Strain Energy Release Rate, $G_{TS}$, for Opening a Colinear Flaw Immediately Ahead of the Primary Crack Tip.
Fig. 9. Total Strain Energy Release Rate, $C_{TS}$, for Opening an Orthogonal Flaw as a Function of the Separation Distance.

Fig. 10. Total Strain Energy Release Rate, $C_{TS}$, for Opening an Orthogonal Flaw as a Function of the Separation Distance and Primary Crack Length.

Fig. 11. Comparison of Total Strain Energy Release Rates, $C_T$, for Primary Crack Propagation Across an Orthogonal Secondary Flaw and Primary Crack Arrest Accompanied by Continued Crack Branching, as a Function of Secondary Flaw Length.

Fig. 12. Influence of Flaw Shape on Total Strain Energy Release Rate, $C_{TB}$, for Crack Branching.
Fig. 13. Crack in Type 304 Stainless Steel Fuel Element Cladding. Direction of Propagation is Toward the ID. Micrograph Courtesy of G. Hofman.

Fig. 14. Comparison of Total Strain Energy Release Rates, G_T, for Primary Crack Propagation Between Two Parallel Secondary Flaws and Primary Crack Branching to Connect with the Secondary Flaws.

Fig. 15. Residual Holes Left by Incoherent Precipitates Removed from Grain Boundaries During Polishing of Type 304 Stainless Steel Irradiated to $1.4 \times 10^{23}$ Neutrons/cm$^2$ at 450-500°C.