CRACK PLANE INFLUENCE ON TIME-DEPENDENT FRACTURE OF BIMATERIALS

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ABSTRACT

The behavior of a crack growing at or near the proximity of a bonded region has historically been approximated and modeled in a somewhat qualitative manner. To quantify how such cracks differ from those within homogeneous materials, parametric computational studies are performed for stationary cracks near a bimaterial interface. Finite element solutions for various compact tension [C(T)] specimen geometries under plane strain conditions are used to judge the limits of applicability of homogeneous creep fracture solutions. The bimaterial model is composed of two distinct isotropic, homogeneous materials that differ only by properties that describe the inelastic behavior. In most cases, an intermediate, finite heat-affected zone (HAZ) is included in the base metal (BM) to weld metal (WM) model. Previous investigations have limited this third material region to assignment of homogeneous properties; this study features a HAZ with a graded blend of base and weld metal properties. This numerical model more closely matches the fused region of actual in-service members, such as seam-welded high temperature steam pipes. Domain integral techniques are used to compute the *C(t)*-Integral and transition times for all cases. Predictions from parametric studies can then be consolidated using curve-fits of crack tip field parameters, transition times, etc. as a function of the HAZ thickness and position, inelastic property mismatches, and other independent model parameters. Results indicate that the incorporation of a functionally graded HAZ region leads to more conservative estimates of the fracture parameters.

KEYWORDS

Fracture, Creep, Functionally Graded Materials, Bimaterials, Finite Elements.

INTRODUCTION

Currently, many studies concerning time-dependent fracture of distinct or welded bimaterials have been limited to cases where the initial crack and its propagation are coplanar with the center of the weld material, Segle, et al. [1, 2]. However, since the predicted states of stress ahead of the crack tip are substantially influenced by the mismatch of properties of the surrounding materials, the nature of the local stress intensity is mixed-modal. The consequence is out-of-plane crack extension.

Functionally graded materials (FGMs) feature continuous variation of one or more material properties across one or more spatial directions. Typically they are interlayers, such as a HAZ, separating two larger material sections, each with negligible property variation. Most investigations that incorporate a transition layer approximate this HAZ with homogeneous properties that are derived from the average of the surrounding base and weld metals. In this study the HAZ is continuously graded in order to achieve more accurate descriptions of the stress and strain situation near the crack tip.

By conducting a parametric study of time-dependent fracture, we develop relationships for the influence of the crack plane-to-interface distance on the *C(t)*-domain integral. Also by obtaining the near tip stress fields, we use approximate means to understand the direction of crack bifurcation.

FINITE ELEMENT MODELING

Until recently, usual bimaterial fracture models were composed of two distinct perfectly-bonded, isotropic, homogeneous constituents. The initial crack was coplanar with their interface. The models used in this study are extensions of those used for the homogeneous case with several modifications. To more accurately represent a typical weldment, for example, models are composed of two bonded homogeneous, isotropic materials, each occupying either the region above or below the crack plane; however, in cases featuring a graded transition layer, a HAZ is introduced in a region between the homogeneous weld and base metal regions. This deviation from the standard homogeneous FEM model requires additional adjustments in the model.

Although the routine used to create these ABAQUS meshes has the capability of producing various model sizes with various stationary crack sizes and far-field and near-tip mesh densities, this study restricts the specimen size, $W = 25.4$ *mm (1.0 in)*, and initial crack size, $a = 12.7$ *mm (0.5 in)*. The thickness is $B = 6.35$ *mm (0.25 in)*. For the time-dependent cases the specimen is subjected to an ambient temperature, $T_a = 538°C$. The model is shown in Fig. 1.

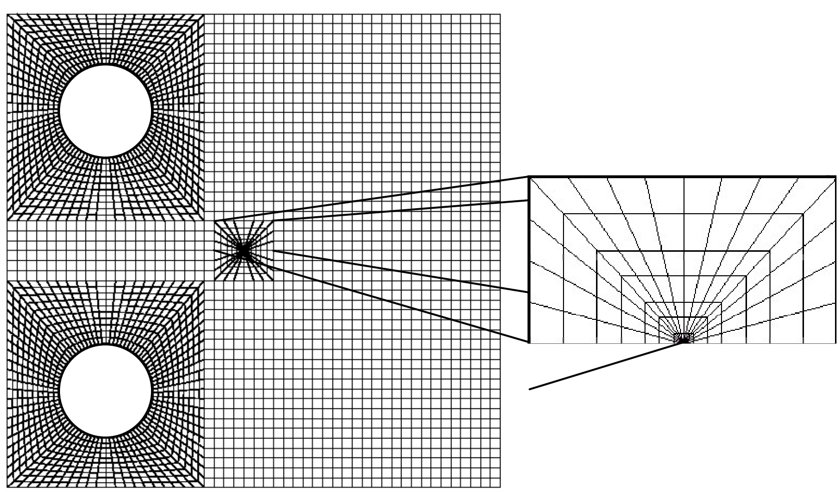

Figure 1: A finite element mesh used in the current investigation.

RESULTING FRACTURE PARAMETERS

In this time-dependent study, elastic-secondary creep behavior models were assumed. Slight variations of the base metal inelastic properties were assumed for the weld, while the HAZ metal was modeled with average properties of the weld and base metals. In every case the elastic properties are identical. The commonly used 2¼Cr-Mo steel exhibits the following properties at close to one-third of its melting point, $T = 538°C$: elastic constants, $E = 160\ GP$ and $\nu = 0.3$, Norton secondary creep constants, $n = 4.7$ and $A = 2.0 \times 10^{-17}\ MPa^{-n}hr^{-1}$.

This elastic match and creep property mismatch should cause changes in the transition time and the steady-state value of the *C(t)*-Integral, *C**, only. Visualizations of the time-dependent effective stress fields were obtained for a variety of models and illustrated in Fig. 2. In the case of weldments, elastic matching permits the stress fields near the material interfaces to be initially symmetric with regard to the crack plane; however, as each of the materials relaxes over time, the steady state stress distribution is not symmetric. This stress re-distribution along each material interface is discontinuous due to the inelastic mismatch and is more intense in the more inelastically compliant, or softer, HAZ and WM regions. For cases where the transition layer or the eccentricity are small but positive, the intensity and variation of the stresses along the interface are greater.

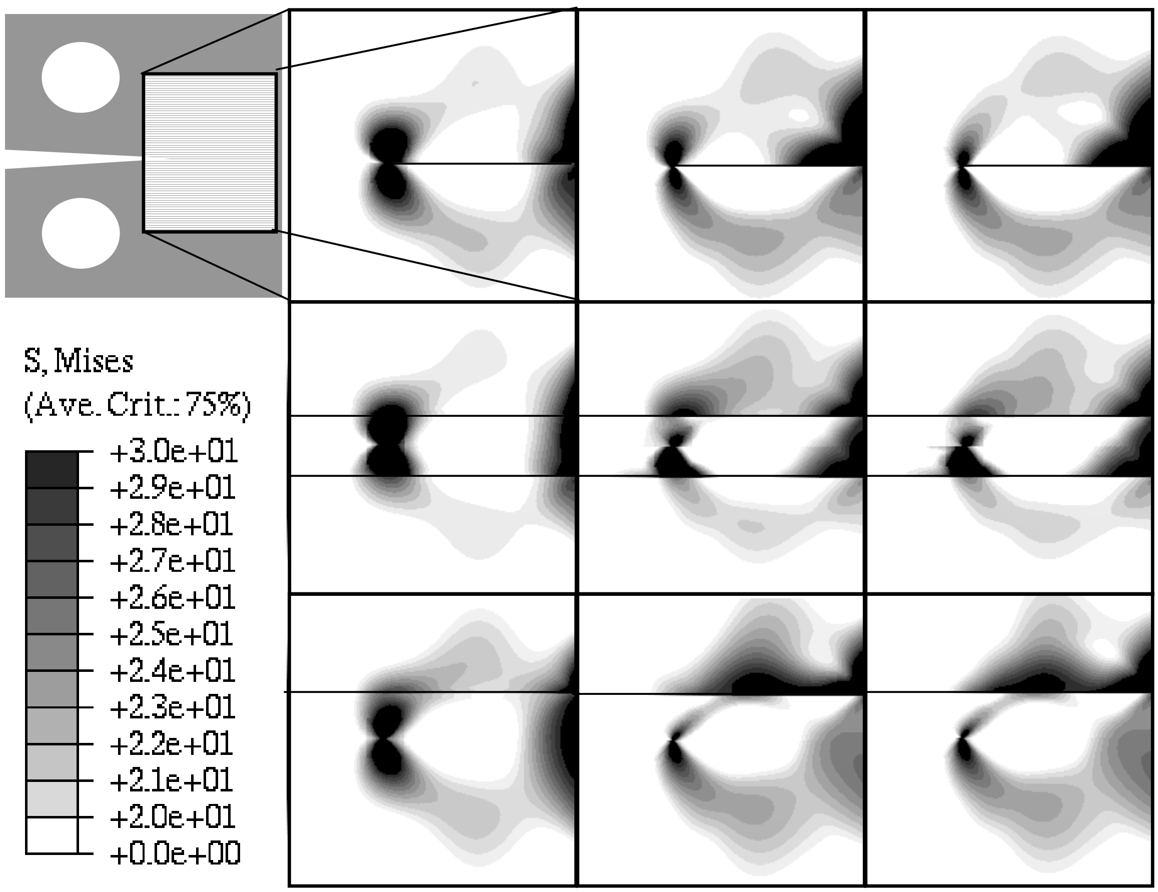

Figure 2: Stress (in ksi) evolution for bimaterial (first row), weldment with blended HAZ (second row), and eccentric bimaterial (third row) specimens. Each weldment specimen features an inelastic overmatch of $\chi_A = 100$ and $\chi_n = 1$ at T = 538°C. For each specimen the effective stress field is shown at various times: $t \approx t_{T_{WM}}$ (first column), $t \approx t_{T_{BM}}$ (second column), $t \gg t_{T_{WM}}, t_{T_{BM}}$ (third column).

For simplicity, it is common to define the material property overmatch, χ, as the weld-to-base ratio of any material property, for example $\chi_A = A_{WM}/A_{BM} = 10$. For each behavior regime, the crack plane distance quantities, eccentricity, e, and transition layer thickness, t, are varied for particular material mismatches. As the eccentricity decreases, the initial crack is embedded more deeply within the base metal. The contour integral approaches values that resemble those of base metal homogeneous model. Likewise, as the eccentricity reaches a large positive number, the C^* converge to C^*_{WM}, respectively. The variation of C^* can be related with a power law. For each of the material mismatch cases for perfect weldments, e = 0, the resulting C^* are observed to nearly follow the logarithmic average of the integral values of two material constituents; furthermore, as the HAZ region thickness increased the contour integral values move towards C^*_{HAZ}, exponentially. For most cases, the fracture parameters can be fit with the following exponential form:

$$\left.\begin{matrix} C^* \\ t_T \end{matrix}\right\} = b(\chi) e^{\frac{D(\chi)}{1.2W} \begin{Bmatrix} e \\ t \end{Bmatrix}}, \tag{1}$$

where b and D are the coefficient and exponent, respectively, which may be obtained explicitly via regression analysis. Each assumes the separate dimensions and should be influenced by the property mismatch. Function b takes on units of the ordinate fracture parameter $\{C^*, t_T\}$, while D is dimensionless. Using this relation, we can quantify b based on the results of the trivial bimaterial model. For $e = t = 0$, this quantity is close to the logarithmic average of the fracture parameters of the homogeneous members, and is usually bounded by these quantities.

FUNCTIONALLY GRADED MATERIALS

Most numerical fracture investigations model transition layers with homogeneous properties. This is not the most accurate depiction of in-service welded members. The majority of investigations that incorporate spatial dependence limit this gradation to only elastic mechanical properties. In a very small number of studies the yield strength is varied. The variation of material properties across a section is usually prescribed according to some linear function of distance. We extend this method to grade the hardening coefficients and exponent of the heat-affected zone.

The HAZ is sandwiched between materials that are homogeneous. Therefore, it is reasonable that the material behavior at each of its boundaries must match that of the weld and base metal. By replacing sharp property variations with continuous material functions, the states of stress and strain in actual service joints and members are perhaps more realistically represented. Micro-hardness tests of welded specimens show that the variation in Vickers hardness changes linearly between base and weld metal regions. Consequently, these sections, which encompass HAZs, correlate to linear yield strength variation from region to region. These indentation profiles, shown by Miyazaki et al. [3], can be combined with either Ramberg-Osgood or

TABLE 1

FRACTURE PARAMETERS FOR VARIOUS HAZ SECTIONS

HAZ Model	Normalized Transition Time, t_T/t_{TBM}	Normalized C(t)-Integral, $C(t)/C^*_{BM}$
No HAZ	0.0216	45.9654
Median HAZ	0.0327	29.4524
FG Linear HAZ	0.0366	25.9942
Base Metal	1	1
HAZ Metal	0.1	10
FG Exponential HAZ	0.0528	18.3862
Weld Metal	0.01	100
FG Continuous HAZ	0.0487	19.1354

Norton power law rules to indicate that the hardening coefficient exhibits exponential spatial dependence across the HAZ. Models with variation of strain hardening coefficient, $A_{HAZ}(y)$, have been simulated under identical boundary conditions. These results are normalized by the homogeneous base metal results. The predicted C^* is higher for models using the blend or median method than models with functionally graded HAZs. Table 1 summarizes this conservative trend.

LOCAL PHASE ANGLE

The mode mixity for a bimaterial is uniquely described by a set of local phase angles. Introduced by Shih [4], the solid angle, ψ, which is also equivalently denoted as the mode mixity parameter, M_p, is found from the interface traction vector. It is given as

$$M_p = \frac{2}{\pi}\tan^{-1}\left[\lim_{r\to 0}\frac{\sigma_{xy}(r)}{\sigma_{yy}(r)}\right]_{\theta=0} . \tag{2}$$

This expression effectively assigns non-dimensional values within the interval *(-1,1)* to distances ahead of the tip of the crack. Since cracks tend to propagate toward the traction vector that is perpendicular to the maximum normal stress, M_p is expected to indicate the direction of crack extension. Isotropic and homogeneous models always produce local phase angles equal to zero. Conversely, when the material constituents on either side of the crack are dissimilar, a non-trivial solution is always obtained. This phenomenon occurs for any material behavior regime. The results of Li et al. [5] show that the singularity fields near the crack tip are mixed mode, and the magnitude of the shearing mode increases with mismatch in properties.

Most investigations into the heterogeneous case have assumed that the crack is not only located on the interface, but is also restricted to growth along the weld line. Only recently have studies progressed to off-weld crack studies. By including this metric in parametric examination of numerically modeled C(T) specimens, we can further understand the influence of the initial position of the crack plane on the time-dependent fracture behavior of bimaterials. The stress fields in time-dependent bimaterials are primarily active between the transition times of the base and weld metals, t_{TWM} and t_{TBM}. This transient behavior is exemplified in M_p for models with various transition layer thickness, t, modeled with blended and functionally graded material properties.

The weld material occupies the upper region in the model; consequently, positive local phase angles indicate that the direction perpendicular to that of the maximum normal stress points toward this more creep strain compliant section. This is the case for each model studied. In Fig. 3, models with a finite HAZ thickness predict local phase angles that would favor crack bifurcation into the direction of the weld metal. When the fracture specimen is simulated with a graded section of some specified thickness, M_p is consistently increased by a factor, which varies based on the bimaterial overmatch. After the transition time of the base metal is reached, M_p smoothly converges to the steady state local phase angle, denoted by M_{pss}.

This technique is also applied to specimens that have eccentrically located cracks. The results indicate that for either negative or positive eccentricities, the local phase angle points toward the more creep strain compliant material. When the crack is located within the base metal (negative eccentricities), these values are (1) increased by at least a factor of two and (2) achieved at times closer to t_{TBM}. In addition, similar to models that include a HAZ, the factor is influenced by the level of the overmatch.

CONCLUSIONS

In addition to other fracture parameters, the mode mixity exhibits slight changes with respect to specimen dimensions and material property mismatch. This traction vector points toward the more compliant material for the subinterface and HAZ thickness models studied. By replacing a blended HAZ with a functionally graded HAZ, the stress concentrations at the interfaces are less extreme and the estimates for the predicted fracture parameters are closer to the reference or base metal; however, the direction of the traction vector is increased by a factor. Collective consideration of a range of thickness or crack plane eccentricity values indicates that the crack is likely to kink into the softer material and then meander back towards the interface. Ultimately, this must be verified by a crack propagation analysis.

Most bimaterial studies limit crack propagation to the direction along the initial crack plane. Future studies featuring crack extension should incorporate propagation along a direction that is controlled by the evolution of the near tip stress and strain fields. The subject matter of interface fracture of non-linear and time-dependent materials needs more attention. Since there is no generalized analytical solution for the variation of the stress, strain, and displacement fields near the crack tip, the results of this study can only be confirmed and extended by performing branching crack analyses and experiments.

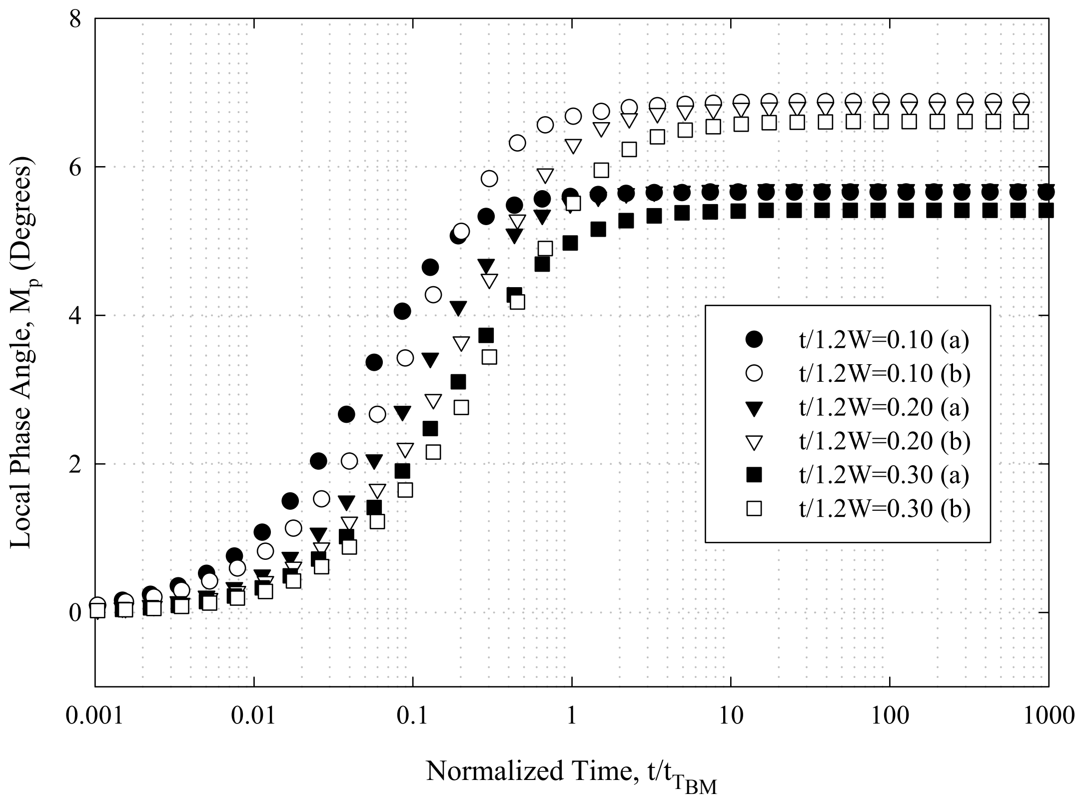

Figure 3: Convergence of local phase angles for median (a) and functionally graded (b) HAZ. χ_A=100 and χ_n=1 for each model.

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