CRACK DEFLECTION IN LAYERED, GRADED COMPOSITES

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ABSTRACT

Crack deflection in discretely layered, graded composites is examined through experiments and finite element modeling. Material and geometric parameters responsible for affecting crack deflection from an existing crack or notch are identified. Fracture experiments with Cu/W graded composites reveal that elastic mismatch between the layers, and layer thickness are key parameters in determining stress fields at the base of a notch. Numerical modeling indicates that the residual stress field, which is a function of the thermomechanical response (thermal expansion, elastic and plastic and behavior), has a significant effect on the crack deflection angle for most situations. These results are discussed in the context of developing predictive models for crack propagation in graded structures.

KEYWORDS

Graded, crack kinking, crack deflection, residual stresses.

INTRODUCTION

The first step in establishing failure criteria for compositionally graded composites is to determine the crack path. For cracks which lie asymmetrically within the gradient, a significant challenge to predicting crack paths lies in the fact that the crack tip stress field and the crack propagation criterion may change as a function of crack length. Thus, understanding which material and geometric parameters control the crack tip stress fields is ultimately required in the development of predictive fracture models for graded materials.

In this work, crack paths are examined experimentally, using Cu/W graded composites. These experimental observations comprise the first part of the paper. The tendency for crack kinking is then examined using a finite element model. The effects of residual stress on altering the crack kink angle are discussed.

EXPERIMENTAL OBSERVATIONS

Cu and W commercially obtained powders were mixed in the appropriate ratios, and layered in a graphite die for hot pressing to produce graded cylinders with discrete layers each consisting of Cu with either 60 % W, 40% W, 20 % W or 0 % W, where percentages are on a volume basis. Higher percentages of W were difficult to sinter to full density. Hot pressing was conducted at 940ºC for 12 h, in vacuum, under an applied load of 40 MPa. Details are available elsewhere [1,2]. The cylinders were cut into mechanical testing bars 3 x 8 x 30 mm, as illustrated schematically in Figure 1. The gradient was symmetric to facilitate mechanical testing. Each layer was either 2 mm or 4 mm in thickness. A 3 mm deep notch was placed using a diamond saw either within the center of the 20% W layer or the 40% W layer. The bar was then placed in four point bending, and the load was increased until a crack propagated from the base of the notch. After the test, the angle of crack deflection away from the loading axis was measured using scanning electron microscopy.

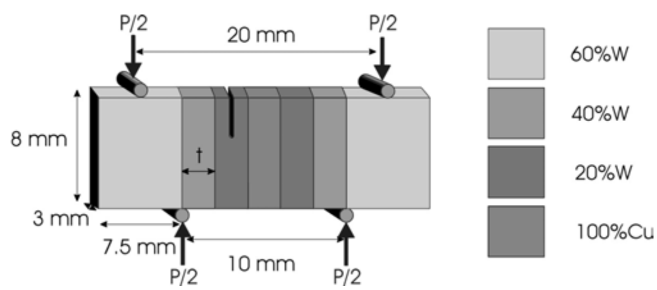

Figure 1: Cu/W graded composite mechanical test specimen. The 100 % Cu composition layer is located symmetrically in the center, to the right of the notch.

Figure 2 shows an example of a fractured bar in which the notch was situated within a 2 mm thick, 20% W layer, similar to the schematic in Figure 1. It is apparent that the crack path is relatively straight, except for the region in the vicinity of the interface between the 20 % W layer and the 0 % W layer, at which point the crack path eventually becomes parallel to the interface. The initial crack deflection angle (that nearest the base of the notch) was measured for each specimen configuration, and the results are shown in Table 1. Each reported measurement consists of an average of 3 tests for that configuration.

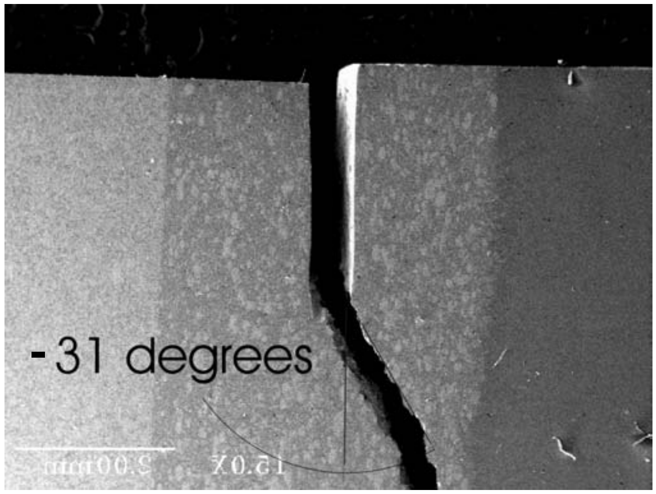

Figure 2: Scanning electron micrograph of bar containing 4 mm thick layers, fractured in four point bending. Notch was cut into 20 % W layer. Crack deflection by 31° towards the more compliant pure Cu layer to the right is apparent.

TABLE 1
Measured Crack Deflection Angles (in degrees). According to the convention used in the FE model, crack deflections towards the more compliant material (towards the right in Figure 2) are negative by definition.

Composition of Layer	Layer Thickness	
	2 mm	4 mm
20 % W	-50	-35
40% W	-25	0

FINITE ELEMENT RESULTS

Details of the finite element model are briefly described here; details are available elsewhere [3]. The commercially available code ABAQUS [4] was used. A four point bend beam (4PB) specimen geometry is analyzed here. The mesh is shown in Figure 3. Incremental FEA is used, allowing the application of mechanical loading to a body that is already deformed by residual stresses. The mesh is 25 mm long and 8 mm high. The discrete compositional gradient is formed by 11mm of pure copper, followed by 1 mm layers of 80%Cu-20%W, 60%Cu-40%W and 40%Cu-60%W, and by an 11 mm section with 20%Cu-80%W; all percentages are volumetric. A crack 3 mm long is cut perpendicular to the gradient in the center of the 60%Cu-40%W middle layer, as shown in Figure 3. Crack tip vicinity stresses resulting from two different conditions are superimposed. First, the thermal residual stresses resulting from thermal expansion coefficient mismatch and a change in temperature are obtained. Second, the stresses resulting from the applied load are evaluated. The residual stresses were obtained by applying an initial temperature of 300^{o}C to all the nodes and subsequently cooling down to 25^{o}C. The applied stresses reported correspond to the maximum stress on the tensile surface of a homogeneous material. Quad second order elements with three nodes collapsed on the crack tip were used. The midside node immediately away from the tip was positioned to a ¼ of the element length to make the element square root singular. Stress intensity factors were obtained from FEA for the residual stresses and for each applied load with and without residual stresses. Standard rules of mixtures were used to estimate material properties [2].

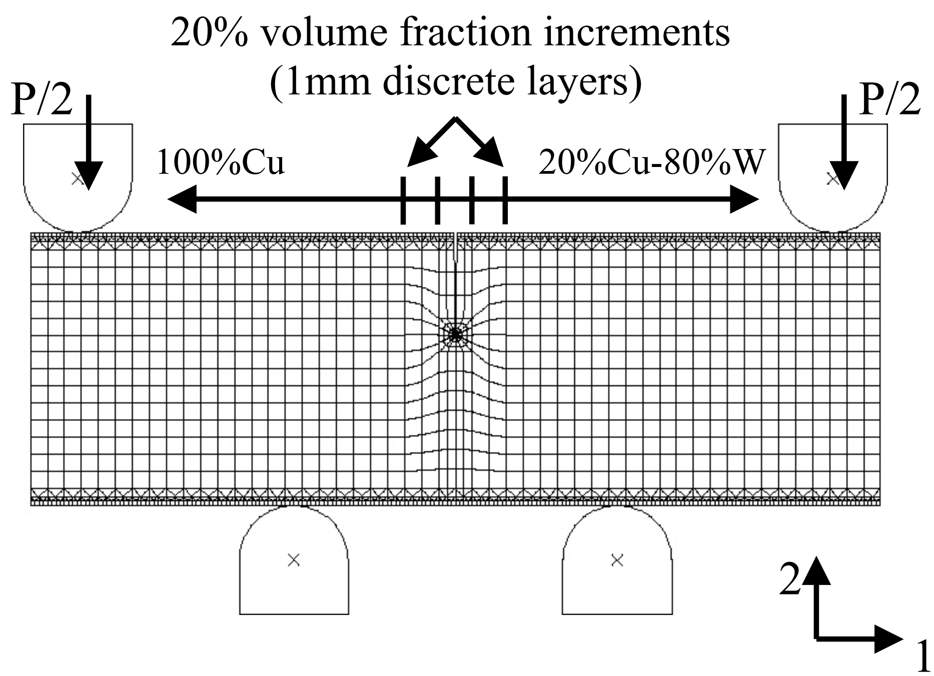

Figure 3: Four point bend (4PB) specimen geometry used for finite element analyses. Extensive mesh refinement is present at the contact surfaces and the crack tip region.

It was observed that the maximum principal stress around the crack tip exhibited a shallow maximum (over about 20°), and thus, a zero shear stress criterion was adopted. By fitting the numerical data with a curve, it was straightforward to determine the kink angle at which the shear stress became zero. It was observed that the predicted kink angle, θ_m, did not depend on the applied stress when no residual stresses were present. However, in the presence of residual stresses, θ_m depended strongly on the applied stress. To relate the results to toughness, the applied mixed mode crack tip stress was converted to an equivalent stress intensity factor [3], and the results plotted as a function of θ_m, as shown in Figure 4.

The dotted line in Figure 4 indicates the predicted value (-6.95°) when there is no residual stress. This value is approached at very high loads (higher than shown here). It is apparent that the effect of the residual stress is to rotate the crack tip stress field such that a positive crack kink angle is achieved for most applied loads. For very tough materials (e.g., $K_{IC} > 25$ MPa $m^{1/2}$), the effect of the residual stress diminishes.

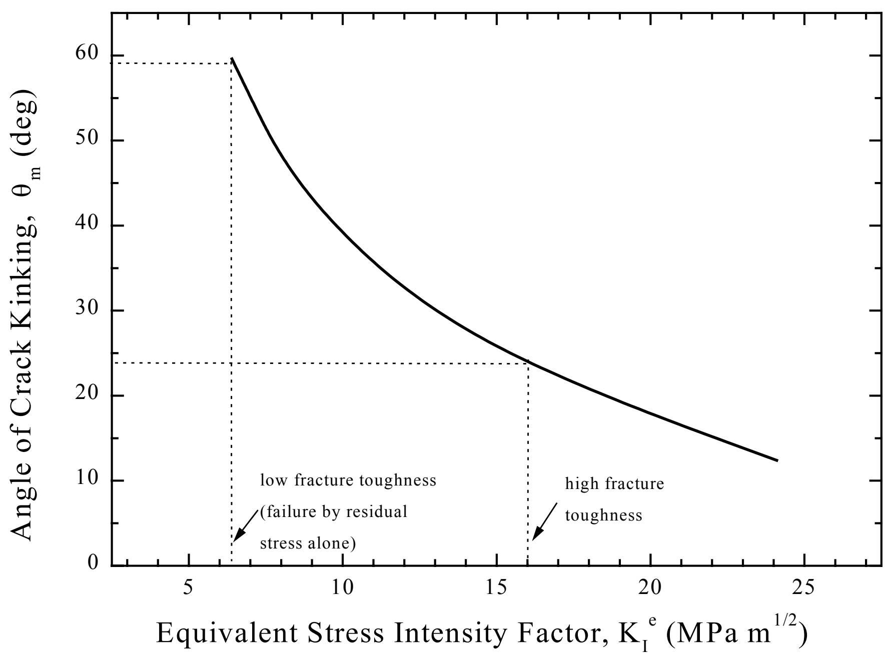

Figure 4: Predicted crack kink angle as a function of effective applied stress intensity factor. The positive crack kinking angles indicate that crack kinking towards the stiffer side of the composite.

The dependence θ_m on the applied stress intensity factor, when residual stresses are considered, is clear when one considers that the total mode I and mode II stress intensity factors are the superposition of the respective residual and applied stress intensity factors. Thus, the residual stress intensity factor rotates the stress field.

Relation of FEM Results to Experimental Observations

Two major differences exist between the experiments and the numerical modeling, making it difficult to compare results between the two. The first is that it is likely that plastic deformation is operative during the development of residual stresses, and during the applied loading, yet it is not accounted for in the numerical model. Second, the FEM specimen geometry is not identical to the experimental four point bend geometry. With these differences in mind, it is realized that the following comments are somewhat speculative.

It is noted that the crack is always experimentally observed to propagate towards the softer and more compliant material. In contrast, the numerical results indicate that in the presence of residual stresses, the predicted crack kink angle is positive, i.e., in the direction of the stiffer, less compliant material. If one assumes that the specimen geometry for the experiment and the numerical model (i.e., compare Figure 1 and Figure 3) is effectively the same, then it must be that plasticity substantially modifies the crack tip stress field. Plasticity is important during the development of residual stresses; obviously, in a graded material, its effect may be non-uniform across the sample, possibly resulting in the rotation of stress fields. Plasticity may also be important during mechanical testing, an effect which would also be asymmetric in a graded material. FE models which account for plasticity in the copper are currently being developed to establish the precise role of plasticity.

CONCLUSIONS

The results here indicate that it is extremely important to take into account the effect of residual stresses when predicting the crack path in a graded composite. In the present case it was observed that without accounting for residual stresses, the crack is predicted to kink towards the more compliant side of the gradient, but in the presence of residual stresses, the predicted crack kink angle is towards the stiffer side. The reasons for this residual stress effect, and the dependence of the crack kink angle on the applied stress are obvious when one considers superposition of residual stress intensity factors and applied stress intensity factors. Specifically, the mode mixity of the residual stress is different from that of the applied stress. The result is that the predicted crack kink angle depends on the material toughness, with tougher materials exhibiting cracks that do not kink as much.

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