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Fracture Testing and Analysis of a Layered Functionally Graded Ti/TiB Beam in 3-Point Bending

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Abstract. This paper presents a methodology for testing and analyzing a layered functionally graded beam consisting of Ti and TiB phases. The test specimen is a single edge notch bending (SENB), with composition varying from a TiB-rich layer at the bottom to commercially pure (CP) Ti at the top. The crack front is aligned parallel to the material gradation and it grows along this direction (mode I). For this crack orientation, "average" R-curve behavior is investigated in order to understand the mechanics of crack growth. The beam is modeled using two-dimensional finite elements considering elastoplastic behavior. Properties of the mixed phase interlayers are approximated using a rule-of-mixtures approach, and the validity of this approach is discussed. Characteristic response quantities are investigated such as the mechanical fields, crack mouth opening displacement, and J integral.

1 Introduction

This paper presents a methodology for testing and analyzing a layered functionally graded beam consisting of titanium/titanium monoboride phases, as shown in Fig. 1. The functionally

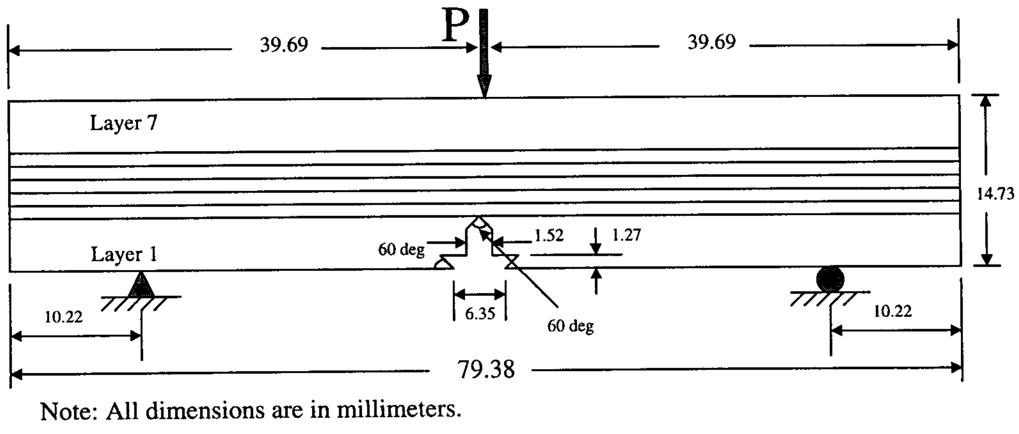

Fig. 1. Seven-layer functionally graded Ti/TiB 3-point bending specimen of thickness 7.37 mm. The corresponding material composition is given in Table 1.

graded Ti/TiB material was prepared by CERCOM Incorporated using a commercially pure (CP) titanium plate and tape cast mixtures of titanium and titanium diboride powders. The final plate was 150 mm square and 20 mm thick, one of the largest FGM specimens produced to date. Details of the manufacturing process can be found in References [1, 2].

2 Experimental Procedure

Single edge notched bend (SENB) specimens were cut from the plate using electro-discharge machining (EDM), with the machined notch on the side containing the highest concentration of titanium monoboride oriented as shown in Fig. 1. The specimens were machined to a width of 14.73 mm, a thickness of 7.37 mm and a length of 79.38 mm with a notch 5.08 mm deep with integral clip gage knife edges in accordance with ASTM E399-90. The machined crack mouth opening displacement (CMOD) gage length was 6.35 mm. Crack mouth opening displacements were measured using an MTS Model 632.03E-30 clip gage. Introduction of a sharp starting crack and the fracture experiments were conducted at room temperature on an MTS 810 servohydraulic load frame running MTS TestStar II control software. Sharp crack initiation was attempted in three point bending fatigue with a starting load of 50 kg, a load ratio of 0.1 (minimum/maximum) and a span of 63.5 mm. Crack growth was monitored by specimen compliance and no growth was noted after 75,000 cycles. The load was increased to 55 kg and application of that load resulted in initiation of a compliance measured crack of 6.29 mm. The resulting specimen was heat tinted at 673K for 60 minutes to mark the length of the actual starting crack. J-R testing was conducted in three point bending in accord to ASTM E1152-87 using a span of 58.93 mm. The compliance of the specimen was determined three times by loading from 9.1 to 27.2 kg. The specimen was then loaded to 36.3 kg at a rate of 2.27 kg/sec, after which the compliance was again measured by unloading by 18.1 kg and reloading. Subsequently, the load was increased by the amount necessary to increase the crack mouth opening by 0.00254 mm and the compliance was again measured by the above procedure. After each load increment, the specimen was held for thirty seconds to allow crack extension to stabilize. The test was terminated after sixteen load increments, after which the specimen was removed from the load frame, heat tinted, and fractured.

The fracture surface is shown in Fig. 2. The initial crack was located in layer #5 (68% Ti/ 32% TiB) and grew in a controlled manner into the middle of layer #6 (85% Ti/ 15% TiB). Figure 3(a) shows a plot of load versus CMOD including the unloading compliance measurement cycles. The increasing compliance values in Fig. 3(b) clearly reveal crack extension with a distinct transition near a CMOD value of 0.02 mm corresponding to the crack front crossing the interface between layers.

3 Finite Element Analysis of Ti/TiB FGM Laminate

Figure 1 shows the layered functionally graded Ti/TiB SEN(B) specimen which was tested and analyzed. To perform nonlinear finite element analysis (FEA), the rule of mixtures was used to estimate the elastic and plastic properties of interlayers for which experimental data are not available [3]. Considering a volume-fraction based interpolation, one obtains the effective modulus of elasticity (E) and uniaxial elastoplastic tangent modulus (H) of the composite as

$$E = \frac{V_\beta E_\beta \left(\frac{q+E_\alpha}{q+E_\beta}\right) + (1-V_\beta)\,E_\alpha}{V_\beta \left(\frac{q+E_\alpha}{q+E_\beta}\right) + (1-V_\beta)} \quad , \quad H = \frac{V_\beta H_\beta \left(\frac{q+E_\alpha}{q+H_\beta}\right) + (1-V_\beta)\,E_\alpha}{V_\beta \left(\frac{q+E_\alpha}{q+H_\beta}\right) + (1-V_\beta)} \quad , \tag{1}$$

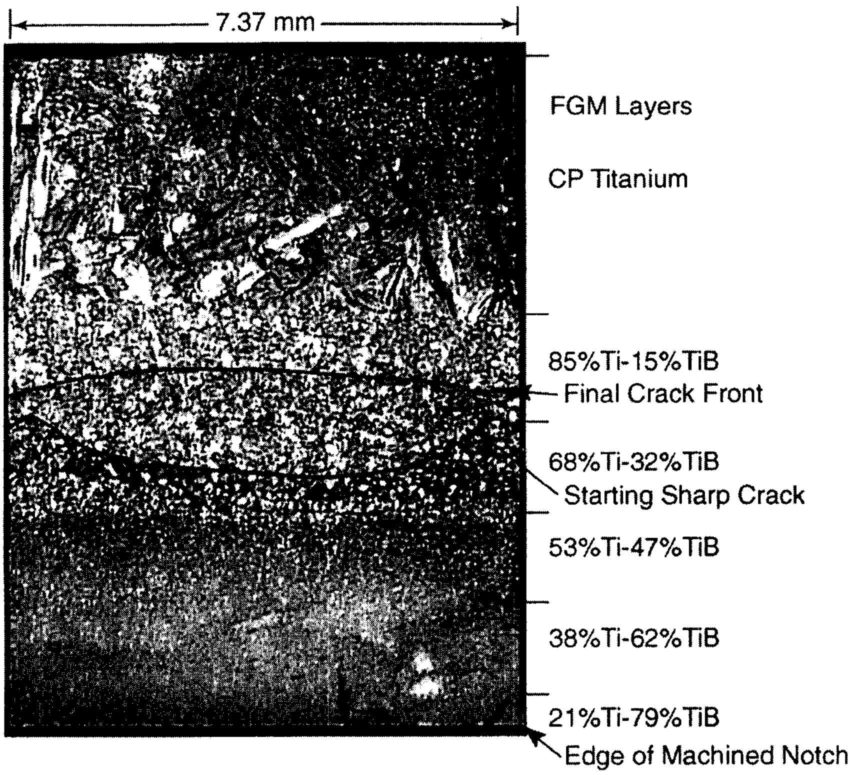

Fig. 2. Ti/TiB FGM fracture surface.

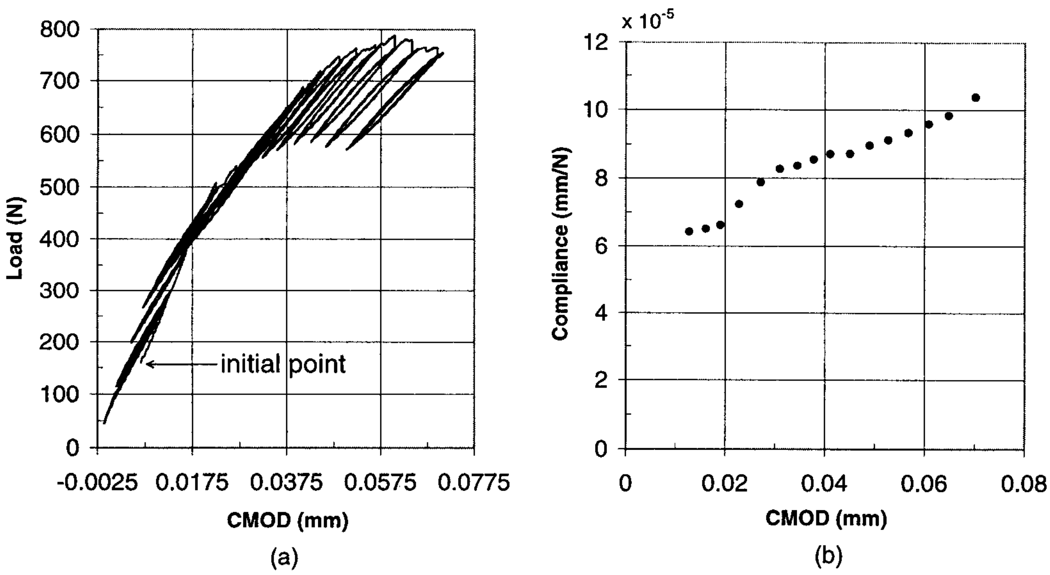

Fig. 3. J-R fracture test results; (a) load versus CMOD; (b) compliance versus CMOD.

where the subscripts α and β refer to the TiB and Ti phases, respectively, V denotes the volume fraction, and q is an important parameter denoting the ratio of stress to strain transfer, given by

$$q = \frac{\sigma_\alpha - \sigma_\beta}{\varepsilon_\alpha - \varepsilon_\beta} \quad , \quad 0 < q < +\infty \quad . \tag{2}$$

where σ and ε refer to true stresses and strains, respectively.

For the Ti/TiB FGM system, a q value of 4,500 MPa has been arbitrarily chosen. This value has been previously used for dual phase steels and Al_2O_3-Ni [3]. Preliminary elastoplastic finite element analyses have shown that the results exhibit some sensitivity to the value of q. Ideally this parameter should be determined experimentally, and work along these lines is currently in progress. Table 1 lists the composition, layer thickness, elastic modulus obtained using Eq. (1), Poisson ratio estimated according to

$$\nu(x) = \nu_\alpha V_\alpha + \nu_\beta V_\beta \quad , \tag{3}$$

and critical J (J_c) for CP Ti and TiB. Note that the J_c values for each of the layers refer to the sub-scale specimen of Fig. 1. Intermediate values of J_c are not calculated according to mixture theory (*e.g.* using an equation analogous to (3)) because it can lead to erroneous results. Estimates of J_c for layers #5 and #6 will be obtained later in this paper by means of both FEA and experimental results.

Table 1. Mixture Theory for FGM Moduli and Poisson ratio.

Layer #	% Ti	% TiB	thick.(mm)	E(GPa)	ν	J_c (N/mm)
	0	100	–	375.00‡	0.140†	0.11†
1	15	85	2.515	274.31	0.170	–
2	21	79	1.676	247.56	0.182	–
3	38	62	1.778	193.68	0.216	–
4	53	47	1.448	162.24	0.246	–
5	68	32	1.753	139.41	0.276	–
6	85	15	2.134	120.07	0.310	–
7	100	0	3.429	106.87*	0.340†	149.73*

*Experimental result obtained in our research group.
†Value obtained from reference [1].
‡Value obtained from reference [2].

Figure 4(a) shows the notation used in the derivation of Eqs. (1) and (2), and Fig. 4(b) shows the stress - strain behavior for the various phases of the Ti/TiB system, which is used as input for the elastoplastic FEA. The present finite element model is designed to capture the crack tip physics as accurately as possible. The finite element mesh to model the beam of Fig. 1 is shown in Fig. 5, which considers an average thickness of 1.7578 mm for the intermediate layers (*i.e.* layers 2 to 6). Plane strain and small deformation theory are considered. Special quarter-point singular elements are used at the crack tip (collapsed Q8), the next layer of elements are quadratic (Q8), then transition, and then linear (Q4). This modeling strategy provides an enriched interpolation scheme which is expected to improve accuracy of the stress and strain fields in the vicinity of the crack tip, and thus also improves accuracy of the computed J integral. The results for applied load versus CMOD and J versus CMOD are given in Fig. 6. Comparison of the upper curve in Fig. 6(a) (crack tip at layer #5) with the experimental results in Fig. 3(a)

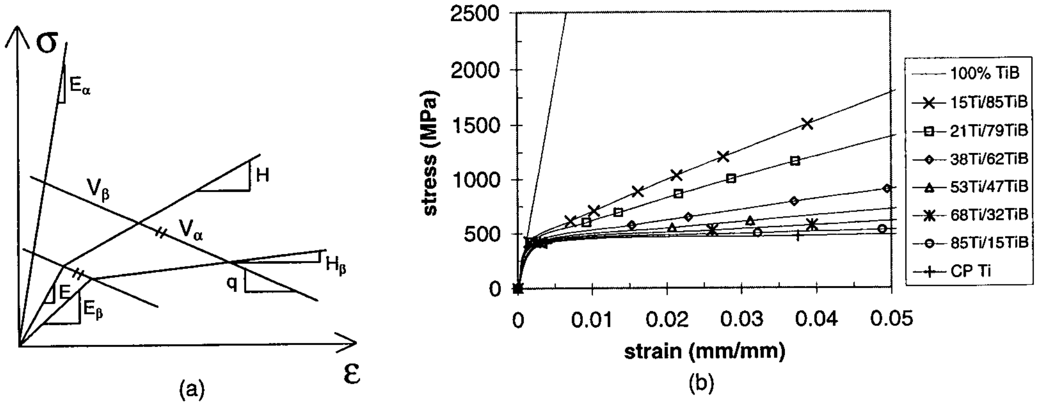

Fig. 4. Stress–strain curves for interlayers of the Ti/TiB FGM system using mixture theory; (a) explanation of notation; (b) actual results.

demonstrates satisfactory agreement. Based on numerical and experimental results, the values for J_c can be estimated as shown in Table 2, where a stands for the crack length and W stands for the beam width (W=14.73 mm).

Table 2. J_c estimates.

Layer #	% Ti	% TiB	a (mm)	a/W	J_c (N/mm)
5	68	32	8.86	0.6	0.28
6	85	15	10.38	0.7	1.59

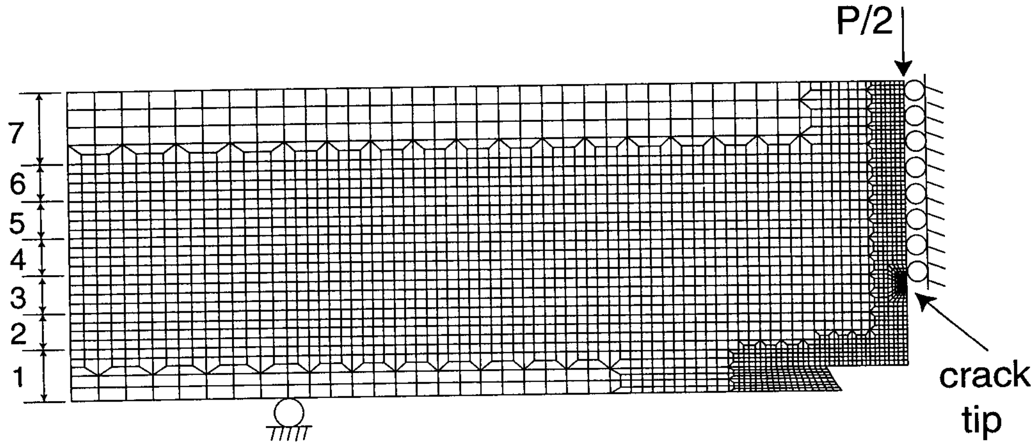

Fig. 5. Finite element mesh for the layered Ti/TiB FGM beam. The numbers on the left (1 through 7) refer to the layers illustrated in Fig. 1 and listed in Table 1.

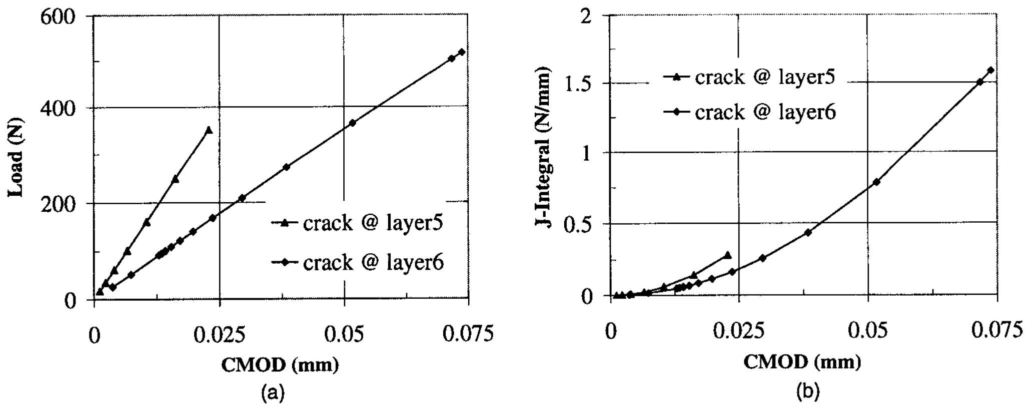

Fig. 6. Finite element results; (a) load versus CMOD; (b) J-integral versus CMOD.

4 Concluding Remarks and Extensions

A testing protocol and analysis for a sub-scale specimen suitable for testing FGM laminates has been presented. The fracture experiments on the Ti/TiB FGM are currently in progress. In particular, further J-R and critical stress intensity factor (K_c) tests will be conducted, which can provide relevant parameters for the FEM model. Tests to determine elastic modulus and fracture behavior of monolithic plates corresponding in composition to two of the FGM laminate layers will also be conducted. These data are needed to properly calibrate the numerical models since the nonlinear mechanical behavior may not follow a simple rule of mixtures for a wide range of material variation. For instance, this work indicates that simple mixture rules are inappropriate for an energy-type quantity such as J. Another important parameter which needs to be determined from experimentation is the ratio of stress to strain transfer (q), given by Eq. (2). Work along these lines is currently being pursued by the authors.

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