CHARACTERIZATION OF INTERFACIAL FRACTURE OF DIFFUSION BONDED BI-MATERIAL JOINTS OF TI-ALLOYS

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This paper presents the effect of the strength mismatch and the elastic *T*-stress on interfacial fracture toughness of bi-material joints. Detailed FE analyses show that both the strength mismatch and the elastic *T*-stress affect near-tip stress fields of the interfacial crack significantly, and thus should significantly affect fracture toughness of bi-material joints. Interfacial crack-tip stresses are quantified in terms of the strength mismatch and the elastic *T*-stress. Experimental verifications based on diffusion bonded bi-material joints of Ti-alloys are in progress.

INTRODUCTION

Fully understanding of interfacial crack tip stress and strain fields is essential for assessment of the integrity of bonded or welded structures and for transferability of laboratory test results to structural components. For homogeneous materials, it is known that the geometry and the mode of loading significantly affect crack tip fields, and thus resulting fracture toughness. Under small scale yielding (SSY), such effect can be accommodated by the elastic *T*-stress (Du and Hancock (1), Parks(2)). However, bi-material interface is intrinsic for many structural components produced by welding or solid-state bonding, and in most of the cases structural performances of such components are limited by fracture along the interface. For such mismatched bi-material joints, it is now fully established that fracture behavior is significantly affected by the strength mismatch between two materials (Schwalbe and Koçak (3), Koçak et al (4)). Thus, the characterization of near-tip stress and strain fields of interfacial cracks are essential to assess structural performances of bi-material joints, which depends on *strength mismatch*

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in addition to the geometry and the mode of loading.

Recently, at GKSS Research Center, the topics of strength mismatch and analyses of interfacial fracture have been intensively studied, e.g., Kim et al (5) and Çam et al (6). The present work is a part of this on-going project and gives the emphasis on the analytical description of interfacial fracture process with accompanying experimental program. In the present work, the effect of the strength mismatch and the elastic *T*-stress on interfacial fracture toughness of bi-material joints is mainly investigated via finite element (FE) analyses. Accompanying experimental work is still in progress and comparison of FE and experimental results will be a topic of next communication.

FE ANALYSES

Effect of Strength Mismatch

Consider *small scale yielding* (SSY) of an interfacial crack lying between two *elastic/perfectly plastic* solids having the *same elastic properties* but *different plastic yield strengths* (Fig. 1). The strength mismatch can be characterized by a mismatch factor $M=\sigma_{Y2}/\sigma_{Y1}$. To investigate the effect of the mismatch factor M on interfacial crack tip fields, finite element (FE) analyses based on J_2 flow theory and small strain formulations have been performed using the boundary layer formulation. Based on the FE results, near-tip asymptotic stress fields have been constructed by patching simple slip line fields, which is depicted in Fig. 2. Such asymptotic stress fields suggest simple relations between M and the stress triaxialities at the interface ($\theta=0$), σ_h/σ_{Y1} at $\theta=0^+$ for the material 1 (lower strength) and at $\theta=0^-$ for the material 2 (higher strength).

$$\left(\frac{\sigma_h}{\sigma_{Y1}}\right)_{\theta=0^+} = \frac{1}{\sqrt{3}}\left(1+\frac{13}{9}\pi - 2\psi_1\right)$$

$$\left(\frac{\sigma_h}{\sigma_{Y2}}\right)_{\theta=0^-} = \frac{1}{M}\left(\frac{\sigma_h}{\sigma_{Y1}}\right)_{\theta=0^+} + \frac{1}{\sqrt{3}}\left(\frac{1}{M}\sin 2\psi_1 - \sin 2\psi_2\right) \quad \text{.......................(1)}$$

In Eq. (1), when $1 \le \mathbf{M} \le 1.8$, $\psi_1 = -0.314\pi(M-1)+\pi/4$, $M\cos 2\psi_2 = \cos 2\psi_1$, but when $1.8 \le \mathbf{M}$, $\psi_1 = 0$, $M\cos 2\psi_2 = \cos 2\psi_1$. Details are given in reference (5). Figure 3 compares resulting triaxialities with the FE results. The mismatch factor M affects interfacial crack tip stress fields significantly. *Increasing* M is associated with *increasing* crack tip stress triaxiality in the lower strength material, but with decreasing triaxiality in the higher strength material. Thus, increasing M will promote ductile fracture in the lower strength material, whereas will suppress it in the higher strength material. According to the experimental observations, provided that bonding is strong, ductile fracture processes (initiation, void growth and coalescence) take place adjacent to the interface in the lower strength material side.

Effect of The Elastic T-Stress

To investigate the effect of the elastic T-stress on interfacial crack tip stress fields, the boundary layer formulation was performed, where two-parameter fields of the Williams' expansion are described. For simplicity, consider bi-materials with extreme strength mismatching ($M=\infty$), i.e., the material 2 in Fig. 1 is elastic. Near-tip asymptotic stress fields are constructed based on the FE results. Figure 4 depicts the effect of the elastic T-stress on asymptotic near-tip stress fields in the plastic material. Full interpretations of such near-tip fields are given in reference (5). Briefly summarizing, results in Fig. 4 provide two remarks. The first one is that the effect of the T-stress on the stress triaxiality in the plastic material is similar to that in homogeneous materials (references (1) and (2)). The second one is that the stress triaxialities for bi-materials are much higher than those for homogeneous materials. Obviously this is due to plastic strength mismatch, as discussed in the previous section. For negative T-stresses, the effect of the T-stress on the stress triaxiality at the interface, can be summarized as follows:

$$\left(\frac{\sigma_h}{\sigma_{Y1}}\right)_{\theta=0^+} = 3.20 + 0.56\left(\frac{T}{\sigma_{Y1}}\right) - 1.97\left(\frac{T}{\sigma_{Y1}}\right)^2 \quad \text{for } M = \infty, \qquad (2)$$

$$\left(\frac{\sigma_h}{\sigma_{Y1}}\right)_{\theta=0^+} = 2.29 + 0.71\left(\frac{T}{\sigma_{Y1}}\right) - 1.10\left(\frac{T}{\sigma_{Y1}}\right)^2 \quad \text{for } M = 1, \qquad (3)$$

Figure 5 supports above two remarks, which compares the stress triaxiality at the interface for bi-materials with those for homogeneous materials.

EXPERIMENTS

Material System, Diffusion Bonding Process and Specimen Geometry

The bi-material system chosen for this study is two titanium alloys: commercially pure titanium (CP-Ti) diffusion bonded to a titanium alloy (Ti-6Al-4V). The uniaxial tensile stress/strain responses for two materials are compared in Fig. 6. The diffusion bonding process begins 58 mm long blanks were cut from 25mm x 25mm bars and machined to produce parallel faces. All the samples were then subjected to similar pre-bonding treatment. The respective samples were bonded at 870°C with a nominal pressure of 3.5 MPa for 1 hour. A micrograph of the dissimilar bond line region indicates that the bond is well-defined (Fig. 7).

The bi-material specimen geometry is schematically shown in Fig. 8. It is loaded in four-point bending. To investigate the effect of M and the T-stress on interfacial fracture toughness, similar and dissimilar bi-material joints with two different crack depths a/W=0.1 and 0.5 are prepared. The testing is in progress, and results will be reported shortly.

CONCLUSIONS

This paper presents the effect of the strength mismatch and the elastic T-stress on (interfacial) fracture toughness of bi-material joints. Detailed FE analyses show that both the strength mismatch and the elastic T-stress significantly affect near-tip stress fields of the interfacial crack, and thus should affect fracture toughness significantly of bi-material joints. Interfacial crack-tip stresses are quantified in terms of the strength mismatch and the elastic T-stress. Experimental verifications based on diffusion bonded bi-material joints of Ti-alloys are in progress.

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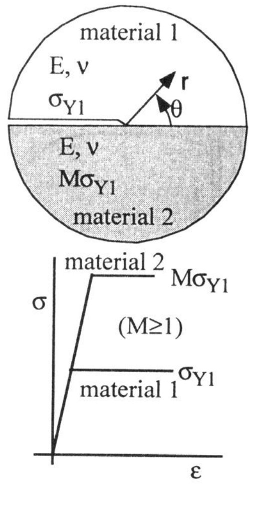

Figure 1 An interfcial crack

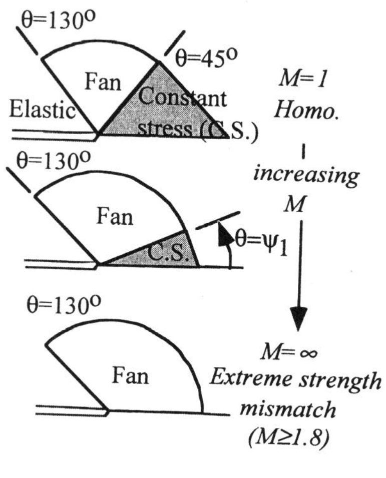

Figure 2 The effect of strength mismatch on asymptotic near-tip fields

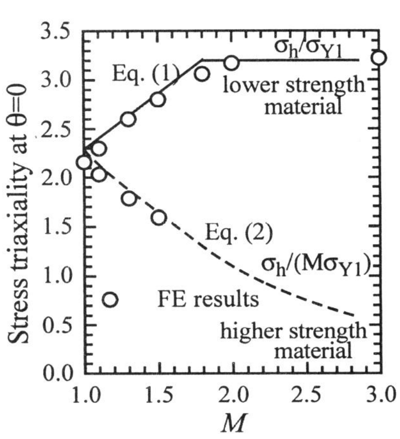

Figure 3 The effect of strength mismatch on interfacial crack tip stress triaxialities

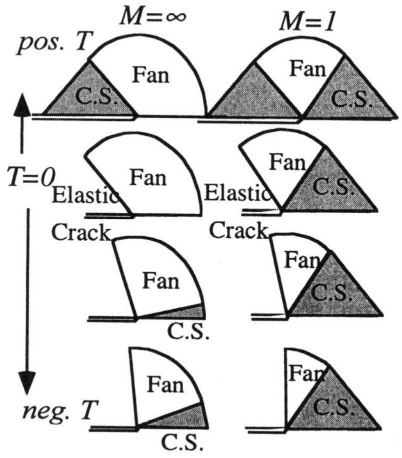

Figure 4 The effect of the T-stress on asymptotic near-tip fields

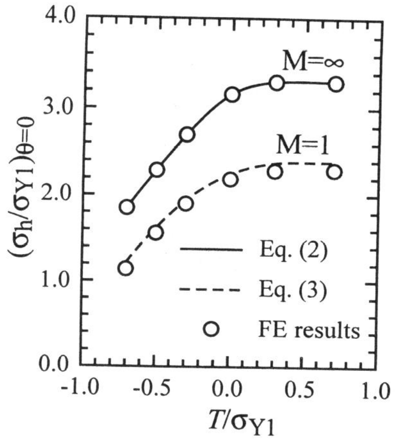

Figure 5. The effect of the T-stress on interfacial crack tip stress triaxialities.

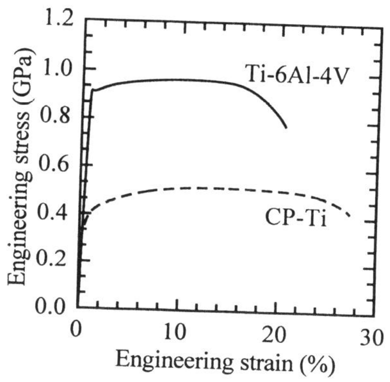

Figure 6 Stress-strain curves for Ti-alloys

Figure 7 Polarized light micrograph showing the bond line

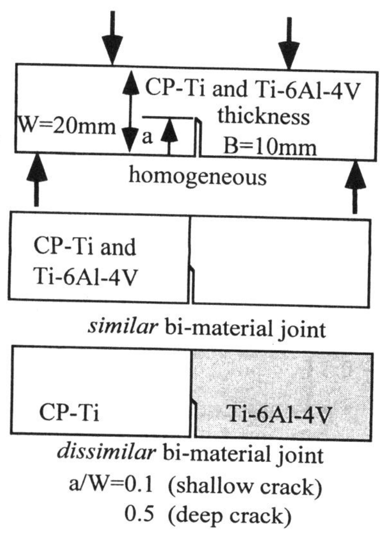

Figure 8 Testing specimen geometries and loadings