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Effect of unbonded areas around hole on the fatigue crack growth life of diffusion bonded titanium alloy laminates

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ABSTRACT

Preformed unbonded areas at the interfaces of diffusion bonded titanium alloy laminates can disturb the stress distribution in their neighborhood, thus changing the crack growing characteristics. We investigated the influence on the crack growth characteristic of unbonded areas' geometric parameters using the extended finite element method (XFEM). First, the effectiveness of the method was validated through the results comparing with experiment. Second, how the unbonded areas' sizes and locations along thickness affect the crack growth was analyzed under tension-tension cyclic loading. The numerical results showed the unbonded areas can effectively block the crack growth, and prolong the fatigue life.

1. Introduction

Titanium alloys are widely used in aeronautical structures for its prominently high specific strength, excellent corrosion resistance and high temperature properties. For example, titanium alloy members, such as load-carrying parts or mechanical joints account for 20% in F35 fighter and up to 40% in F22 fighter. Although exhibiting excellent properties, titanium alloys are susceptible to initiated cracks, i.e., its residual crack growth life is dramatically short after a crack occurs, which is unacceptable for aeronautical structures.

Apparently, an effective way to improve the damage tolerance of titanium alloys is through material composition or inner microstructure design. So far, titanium alloys having different compositions and microstructures have been fabricated and their crack growth behaviors were tested to show their improved crack growth resistance [1–8].

Alternatively, the design of titanium alloys structures can be modified to prolong its crack growth life by providing crack path turning or arrest and crack retardation. For example, drilling stop holes in the vicinity of the crack tips is an effective way to arrest fatigue crack propagation. Makabe et al. [9] suggested that inserting pins into stop holes is more efficient to retard crack growth. Orifici et al. [10] proposed that introducing small special flaws into composite laminates can control growth of interlaminar cracks and through-thickness crack branching. Llopart et al. and Uz et al. [11–13] found that the stress intensity factor (SIF) distribution can be modified for a center cracked flat stiffened panel via a variation of stringer cross-sections or thickness of both skin sheets and stringers, which in turn the crack growth life was improved. Therefore, it is feasible to find an effective design to improve the crack growth life of titanium alloys structures.

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Nomenclature

a_t	the crack length along the thickness in the specimen
a_w	the crack length on the surface of the specimen
C	Paris constants
E	Young's modulus
G	the strain energy release rate
K	the stress intensity factor under loading
K_{th}	the threshold of material
$K_{\max}$	the largest stress intensity factor under loading
K_{IC}	fracture toughness under mode I loading
n	Paris constants
N	the fatigue life of the specimen from the precrack to failure
R	stress ratio

Greek letters

σ_b	ultimate strength
σ_m	the max stress under loading
ν	Poisson's ratio

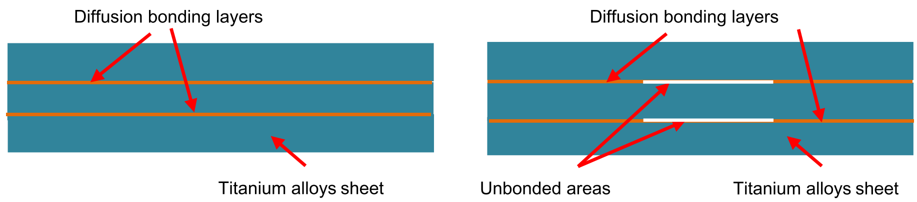
Diffusion bonding is a solid state bonding technique without the presence of a liquid phase [14,15]. Recently, diffusion bonding technique has also been used to obtain multilayer metal materials [16], which is dependent on various parameters, in particular, time, applied pressure, and bonding temperature to promote microscopic atomic movement to ensure complete metallurgical bond. Titanium alloy laminate is manufactured by diffusion bonding of several thin titanium sheets and therefore the thickness and number of sheets becomes design parameters, which is more flexible to meet different structural demands. A typical diffusion bonded titanium alloy laminate (DBTAL) is shown in Fig. 1, where there exists a diffusion bonding layer (DBL) between two adjacent titanium alloy sheets. The presence of DBLs in DBTALs may change the crack growth path and thus improve its fatigue crack growth life. However, DBL is very thin and therefore its contribution to fatigue crack growth life is limited.

Due to the laminate structure of DBATL, it is possible to insert special flaws into DBLs to interfere the crack growth. He et al. [17] embedded a localized unbonded (no-welded in [17]) area around a drilled hole in a DBATL. The tension-tension fatigue experiment results showed that the crack growth rate (da/dN) was slowed down when the crack tip reaches the unbonded area. The crack growth path was turned, i.e., the crack had to bypass the unbonded area. Consequently, it indicates that introducing unbonded area in the DBL may be a possible solution to prolong the fatigue crack growth life of DBATL.

In our previous work [18], the extended finite element method was employed to simulate the crack growth behavior of titanium alloy laminates with unbonded areas around hole subjected to tension-tension cyclic loading and validated by experiment results in [17]. In this paper, this numerical method was further validated by our experiment results. The effect of size and location of unbonded areas around hole on the crack growth behavior of DBTAL was then parametrically analyzed and numerical results suggested that insertion of unbonded areas into DBTALs can effectively improve its fatigue crack growth life.

2. Fatigue testing of the DBTAL specimen with unbonded areas

For a flawless plate, the initial crack location is always unknown due to the uncertainty of the material or the manufactory process. To simplify the problem in this paper, an open-hole specimen under tension-tension cyclic loading was adopted, and the unbonded areas are introduced to the open-hole locations. Hole edge always tends to initiate cracks under the action of



(a) The schematic of through-thickness direction in laminate
(b) The laminate with unbonded area

Fig. 1. The schematic of diffusion bonded titanium alloy laminate.