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Fatigue crack growth in diffusion-bonded Ti-6Al-4V laminate with unbonded zones

Xiaofan He [a,*], Yinghao Dong [a], Yuhai Li [b], Xiangming Wang [c]

[a] School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China
[b] Aviation Industry Corporation of China, Beijing 100022, China
[c] Shenyang Aircraft Design Institute, Shenyang 110035, China

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ABSTRACT

Fatigue crack growth (FCG) tests were conducted to investigate the behavior and laws of crack growth in diffusion-bonded laminates of Ti-6Al-4V (2 mm + 2 mm + 2 mm + 2 mm) with three unbonded zones, the initial crack being a semi-elliptical surface crack. Post-test fractographic analyses indicate the crack growth in the laminate characterized by four distinct stages. The crack initially propagates in the first layer as a semi-elliptical surface crack (Stage I). After the surface crack penetrates the first layer, the crack becomes a through crack, which continues propagating in the first layer (Stage II). When the through crack arrives at the boundary of the first unbonded zone, it evolves into a part-through crack, during which crack growth rate keeps decreasing (Stage III). After that, the crack propagates as a part-through crack until the laminate fractures (Stage IV). It also indicates that the crack-growth-deceleration effect of the first unbonded zone is of more significance compared with the other unbonded zones. With the marker bands on the fractography, FCG data was obtained. Then we used the finite element method to calculate stress intensity factors for the laminates and obtained the relationship between FCG rate (da/dN) and stress intensity factor range (ΔK). The analysis on the $da/dN - \Delta K$ curve shows that the decrease in ΔK is an important factor, although not the sole factor, contributing to the crack growth deceleration near the boundary of the unbonded zone.

1. Introduction

Ti-6Al-4V, as an $\alpha + \beta$ alloy, has good corrosion resistance, high specific strength and excellent weldability, justifying its wide utilization in aerospace, shipbuilding, petrochemical and automotive industry [1–3]. However, titanium alloy is difficult to machine and expensive to use. To reduce the cost of processing, multiple forming processes have been developed since the 1950s, with diffusion bonding being a significant part of it.

Diffusion bonding (DB) is a solid-state bonding process, during which bonds at atomic level are formed due to microscopic plastic deformation and diffusion of atoms between two solid surfaces in intimate contact under controlled conditions of time, temperature and pressure [4,5]. There is no heat affected zone or macroscopic deformation associated with the bond, resulting in accurate dimensional control. This allows diffusion bonding to be successfully applied in titanium alloy forming.

The diffusion-bonded laminate of Ti-6Al-4V (hereafter referred as Ti64) is a typical titanium-alloy structure, with the manufacturing process shown in Fig. 1. The large bond area associated with the laminate is likely to lead to interfacial defects, thus compromising bond strength. Many investigations have been conducted over the effect of interfacial defects on the strength of diffusion-bonded titanium alloy structures. Zhu [6] studied the influence of void ratio and maximum defect size on the joint strength, and produced the minimum void ratio and defect size that can adversely affect the fatigue strength of DB joints. Cepeda-Jiménez [7] examined the effect of interfacial defects on the shear strength and fracture toughness of DB laminates of Ti64. Wu [8] proposed that inclusions in the interface were responsible for the decrease in fatigue strength of DB joints. It also indicates that small single voids in the interface are insignificant, but clusters of voids can remarkably reduce fatigue life [9,10]. For a long time, researchers have been engaged in optimizing the diffusion bonding process to eliminate interfacial defects. However, interfacial defects are inevitable for diffusion-bonded laminates.

Conventionally, interfacial defects can reduce structural strength. Experimental studies have shown that fatigue strength

* Corresponding author.
E-mail address: xfhe@buaa.edu.cn (X. He).

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Nomenclature

a	half-crack length
a_1	distance of the outmost point on the left crack front from y-axis
a_2	distance of the outmost point on the right crack front from y-axis
C	coefficient in Paris-Erdogan law
m	number of a vs. N pairs in a data set
n	exponent in Paris-Erdogan law
N	number of load cycles
R	stress ratio
ΔK	stress intensity factor range
$\Delta K_{\min}$	the minimum of stress intensity factor range
CA	constant amplitude
DB	diffusion bonding
FCG	fatigue crack growth
FE	finite element
FEM	finite element method
OM	optical microscope
SEM	scanning electron microscope

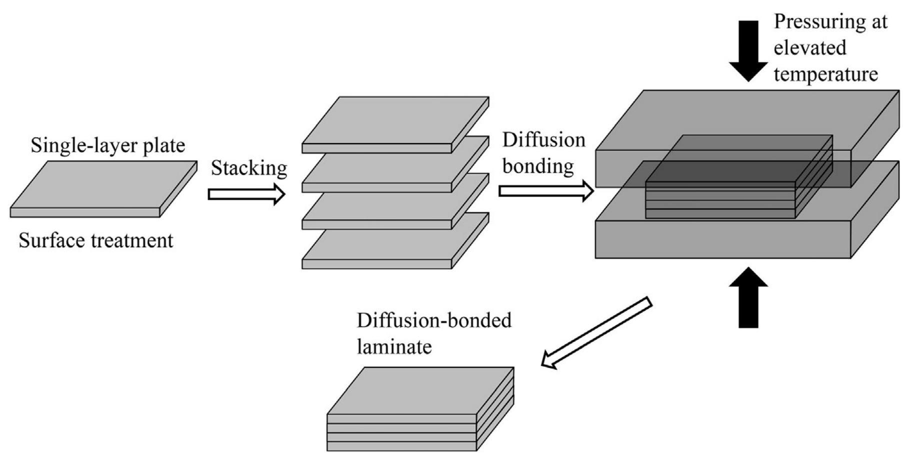

Fig. 1. Schematic of the manufacture of diffusion-bonded laminate of Ti-6Al-4V.

of DB laminates of titanium alloy can be adversely affected by the interfacial defects when out-of-plane loads (i.e. loads perpendicular to the interface) apply [6,8,10]. However, under the condition of in-plane loads (i.e. loads parallel to the interface), the effect of interfacial defects is insignificant [11–13]. Therefore, DB laminates of titanium alloy are suitable for applications sustaining in-plane loads, such as beam and flange.

Damage tolerance of structures receives much attention due to its critical role in safeguarding structural safety and economy of aircraft. Titanium alloy is known for its good fatigue strength but unsatisfactory damage tolerance property [14,15]. To improve the damage tolerance property of DB laminates of Ti64, Wang [16] developed a novel laminated structure, DB laminate with unbonded zones as shown in Fig. 2. Solder-resistant powder is placed between the mating surfaces prior to diffusion bonding,

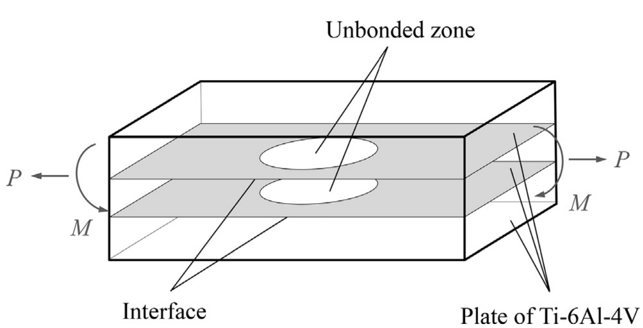

Fig. 2. Diffusion-bonded laminate with unbonded zones under in-plane loading.

and laminates with localized unbonded zones can be made through diffusion bonding [17]. This concept abandons the zero-defect interface that has always been sought, and intentionally enlarges the interfacial defects. According to the design concept associated with the back-to-back structure [18], large interfacial defects are expected to retard crack growth under in-plane loading, and the fatigue crack growth (FCG) life can thus be extended.

To verify the beneficial effect of the unbonded zone, fatigue tests were performed for the DB laminate of Ti64 with a centered hole and circular unbonded zones under in-plane cyclic loading [13,19,20]. The test results show that FCG rate decreases as the crack bypasses the boundary of the unbonded zone. FCG simulations were made for the DB laminate with unbonded zones [21–23]. The simulations also illustrate the beneficial effect of the unbonded zone.

Obviously, DB laminates of Ti64 with unbonded zones have good damage tolerance property. As design is allowed over the shape, size and position of the unbonded zone, the damage tolerance property is expected to be further improved through optimal design, which drives an urgent need for understanding the FCG behavior and FCG laws for the DB laminate with unbonded zones. To achieve this end, we first performed FCG tests for DB laminates of Ti64 with unbonded zones under in-plane tensile cyclic loading. With the aid of marker load, the whole process of crack growth was reconstructed. Second, quantitative fractographic analyses were conducted under the optical microscope and the scanning electron microscope, with the macroscopic and microscopic FCG behavior illustrated. Third, stress intensity factors were calculated for the crack fronts observed on the fractography, followed by an analysis of the variation of stress intensity factor range with crack length.