Materials Letters 112 (2013) 47–50

Contents lists available at ScienceDirect

Materials Letters

journal homepage: www.elsevier.com/locate/matlet

In-situ scanning electron microscopy studies of small fatigue crack growth in ultrasonic consolidation bonded aluminum 2024 laminated structure

Xiao-Hua He [a], Hui-Ji Shi [a,*], Yu-Duo Zhang [b], Wen-Xiang Fu [b], Zhi-Gang Yang [b], Carey E. Wilkinson [c]

[a] AML, School of Aerospace, Tsinghua University, Beijing 100084, China
[b] Key Laboratory for Advanced Materials of Ministry of Education, School of Materials Science and Engineering, Tsinghua University, Beijing 100084, China
[c] The Boeing Co., USA

ARTICLE INFO

Article history:
Received 27 May 2013
Accepted 22 August 2013
Available online 30 August 2013

Keywords:
Aluminum alloy
Fatigue
In-situ SEM
Interface
Microstructure

ABSTRACT

This work used in-situ scanning electron microscopy method to investigate the small fatigue crack behavior of the aluminum alloy 2024 laminated structure produced by ultrasonic consolidation process. The influence of local microstructure on the crack propagation of the laminates after different heat treatments (T4 and T62) has been compared and discussed. It was found that both the precipitations and the interfaces of the layers could retard crack growth and alter the growth direction, and the effect of interfaces was much stronger. Due to the higher ratio of the toughness to bond strength, the barrier effect of the interfaces on impeding the fatigue crack growth in specimens after the T4 heat treatment was more evident.

1. Introduction

Laminated metal structures have been utilized as structural materials in aerospace, navigation and defense industries due to their improvement in various properties, e.g. fracture toughness, impact behavior, wear and damping capacity [1–6]. As an innovative solid-state manufacturing technology, ultrasonic consolidation (UC) process has a number of advantages over the traditional techniques, e.g. internal geometry capability, reduction in residual stresses and consumed energy [7–9], and also allows embedding fibers, wirings and electronics sensors into the laminates to make smart materials [9–11]. Most of the investigations of laminated structures were focused on the fracture and impact toughness and different toughening mechanisms [2–6], but the fatigue properties were limited studied [12–14]. Besides, the researches so far on the laminates produced by the UC process were concentrated on the optimization of parameters by peel test and microstructure observation [9,15–22], but the studies on the mechanical properties were scarce and not in-depth [10,23], let alone the fatigue property.

In this study, the in-situ SEM technique was used to investigate the small fatigue crack growth behavior in the UC produced Al 2024 laminated structure after different heat treatments (HT). Particular emphasis is placed on examining the fatigue cracking mechanism and the effect of local microstructure on crack growth.

2. Materials and experimental details

The nominal composition of Al 2024 alloy is (in wt%): 0.5Si, 0.5Fe, 3.8–4.9Cu, 0.3–0.9Mn, 1.2–1.8Mg, 0.1Cr, 0.25Zn, 0.15Ti and Al balance. Specimens were cut with gauge length parallel to the longitudinal orientation of the metal foils. The slab specimens had a dog-bone shape with a 1.4 mm by 1.5 mm gauge cross section and a U-shaped notch was prepared by WEDM. The specimens were divided into two groups and heat-treated to a T4 and a T62 temper, respectively. The surfaces of all the specimens were polished and then etched in a solution of 1% HF + 1.5% HCl + 2.5% HNO_3 + 95% H_2O to reveal the microstructure.

Optical microscopy (OM) and scanning electron microscopy (SEM) were performed to observe the microstructure of the laminated structure after etching. The in-situ fatigue tests were performed at room temperature (RT) in the vacuum chamber of the SEM using a specially designed servo-hydraulic testing system. A maximal stress of 300 MPa was adopted throughout the tests for all specimens. The load waveform utilized was sinusoidal with stress ratio $R=0.1$ and frequency $f=5$ Hz.

* Corresponding author. Tel.: +86 10 62772731; fax: +86 10 62781824.
E-mail address: shihj@mail.tsinghua.edu.cn (H.-J. Shi).

0167-577X/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.matlet.2013.08.093

3. Results and discussion

Fig. 1 presents the OM and SEM observations of the microstructures on a cross-section of the laminates. No matter after T4 or T62 HT, the laminated structures contained a few small defects but no initial delaminations at the interfaces (Fig. 1b and e). The grain sizes of the specimens were not uniform, and there was no obvious difference of the grain sizes between the specimens after T4 and T62 HT. Generally, the grains near the interfaces were much smaller, as shown in Fig. 1a and d. Moreover, precipitation compounds were widely distributed in the grains, as indicated in Fig. 1c and f.

The typical microstructure of Al 2024-T4 alloy laminated specimen is shown in Fig. 2a. The prepared U-shaped notch was 188 μm in depth and 485 μm in diameter. Fig. 2b depicts the initial fatigue cracks from the notch root and the precipitations after over 23,000 cycles. It was noticed that the crack did not break the precipitations but tended to change its path and bypass the small blocky precipitation. After exceeding about 60 μm in crack length, some slip traces were observed along with the crack propagation and an obvious slip trace appeared in front of the main crack (Fig. 2c). As the crack propagated along this slip trace, a subsurface precipitation was revealed, as indicated in Fig. 2d, which explained why the slip trace appeared preferentially at that site.

The interface of foils is a unique part in the laminated structure. Thus the influence of interfaces on the crack growth of the laminated specimens is of great concern. The main crack was blocked after approaching the first interface. During the following 2000 cycles, the propagation of the fatigue crack was divided into two directions, i.e. the transverse one and the longitudinal one as shown in Fig. 2e. At this stage, the longitudinal crack along interface was dominated and propagated faster. Meanwhile, the prior main crack continued to impinge the interface and its crack tip opening displacement (CTOD) visibly increased, indicating evident effect on retarding the growth of the transverse crack. This retardation by local interface delamination has also been

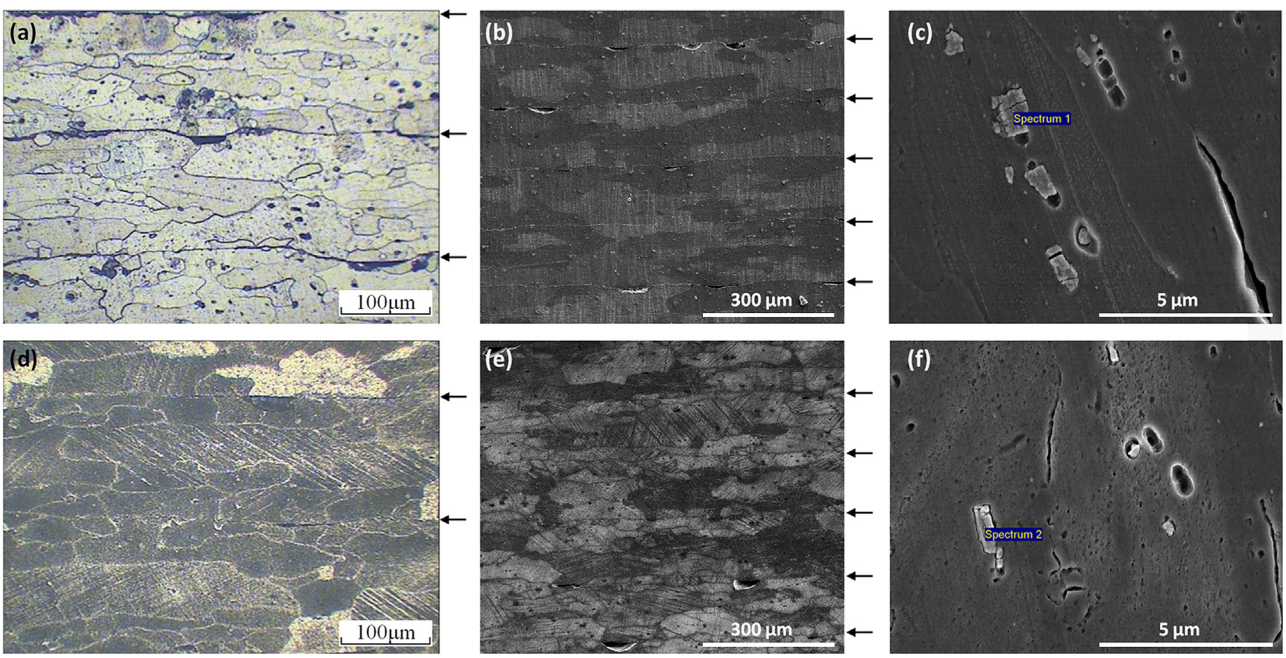

Fig. 1. OM observations, SEM observations and precipitations of the laminated structures after T4 HT (a)–(c) and after T62 HT (d)–(f). (The black arrows indicate the locations of interfaces.)

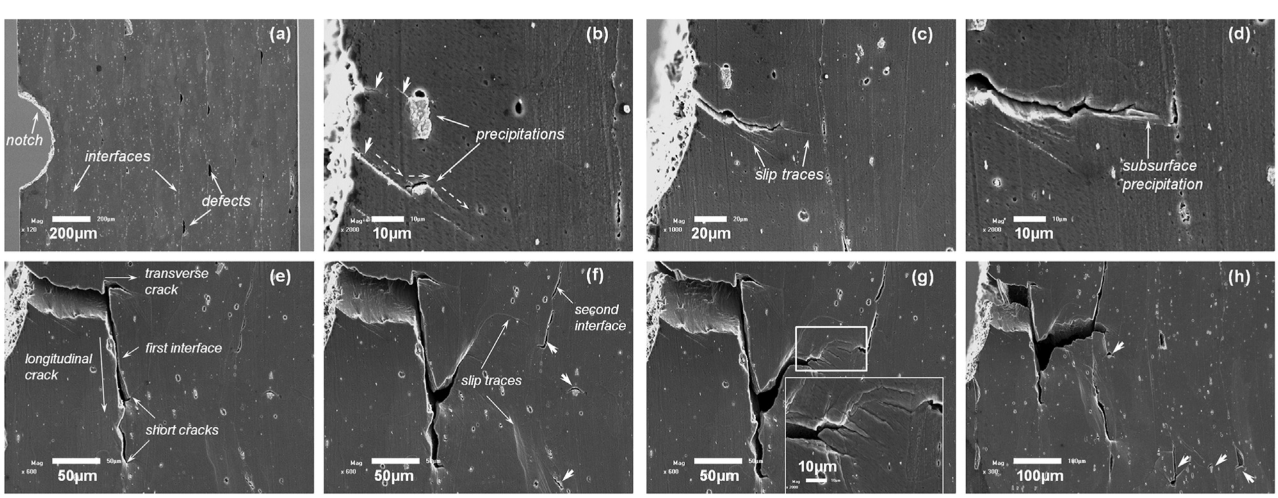

Fig. 2. Fatigue short crack growth in Al 2024-T4 laminated specimen. (a) 0 cycles; (b) 22,954 cycles; (c) 25,414 cycles; (d) 25,730 cycles; (e) 27,925 cycles; (f) 28,241 cycles; (g) 28,399 cycles; and (h) 28,837 cycles.