EFFECT OF HYDROTHERMAL AGING ON FRACTURE PROPERTIES OF BONDED TITANIUM JOINTS

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ABSTRACT

Fatigue delamination is a major concern for titanium laminate composites, particularly at elevated temperatures. Research has been conducted to investigate the durability of bondlines in titanium laminates following long term hydrothermal exposure. In an effort to determine the optimal titanium-polyimide bond for high-temperature in adverse conditions, Ti-15-3 cracked lap shear specimens were tested with combinations of two different polymeric resins with three different commercially available titanium surface treatments in a variety of exposure environments. After 10,000 hours in both hot (177°C) dry and hot wet conditions, the specimens were fatigued at constant amplitude to demonstrate the optimal resin/surface treatment combination. As was determined by Cobb and Johnson [1] for higher temperature tests after 5,000 hours, Ti-15-3 treated with Boeing's Sol Gel surface preparation and subsequently bonded together using FM5 polyimide proved the most durable combination. Furthermore, as expected, most combinations exhibited more accelerated fatigue crack growth in the wet condition then the dry condition.

KEYWORDS

Fatigue, bond, titanium, surface treatment, delamination, elevated temperatures.

INTRODUCTION

Modern aerospace researchers still endeavor to design aircraft that fly faster and longer then ever before. Such advancement is contingent upon materials capable of operating at long lives (> 10,000 hours) and high temperatures while being fatigue resistant and damage tolerant. Hybrid Titanium Composite Laminates (HTCL) are a type of hybrid composite laminate designed specifically for this purpose and these mechanical properties. Hybrid composite laminates consist of varying layers of metal alloy (in this case titanium for 177°C durability) bonded with layers of polymeric matrix composites (PMC) to produce a high-performance, fatigue-resistant material, retaining the strength-to-weight gains of fiber composites. However, for the damage tolerance to be realized in such a material, stable, controlled delaminations must be achieved. The development of hybrid composite laminates originated following the success of extensive lamination research. In 1967, J. Kaufman [2] proved that a laminate of adhesively bonded aluminum plies has nearly twice the fracture toughness of a single aluminum plate of the same overall thickness. In 1978, W. S. Johnson, et al. [3] demonstrated the increased fatigue and crack growth resistance of laminated aluminum. Johnson [4], in 1983, proved these increased damage tolerant properties also characterized adhesively bonded titanium. By the mid-1980's, Delft and ALCOA developed the first hybrid composite laminate called ARALL. [5] The material is composed of thin aluminum laminae with aramid fiber reinforcing the bondline. The premise of the design was to retain the damage tolerance and fracture toughness demonstrated in metal laminates, while incorporating the mechanical advantage the fibers offer to strengthen the material and contribute to crack growth resistance of the metal. After the initial success of ARALL, GLARE was developed in 1991, which uses R and S2 glass instead of aramid as the fiber [6]. These materials are now flying on several commercial and military aircraft. HTCL was developed by Johnson, Miller, and colleagues [7] in the mid-1990's for the same benefits, only for high-temperature (177° C) applications. With the preliminary testing proving successful, subsequent, extensive testing was started by Li and Johnson [8] in 1996 to demonstrate HTCL's fatigue resistance at elevated temperatures.

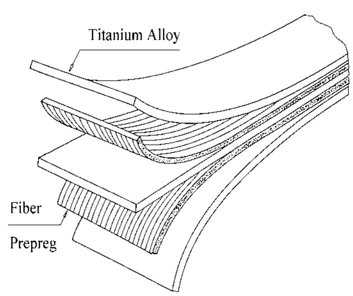

Figure 1. HTCL

However, the results showed that HTCL consistently debonded at the titanium/polymer interface following a fatigue crack forming in a titanium layer. For the fibers to adequately "bridge" the titanium crack, only a moderate amount of delamination can occur between the layers. In order to limit such damage, efforts began to determine ways to increase the strength of the titanium/PMC interface. The primary method to improve bond strength and durability is to prepare the surface of the titanium. The surface treatment produces a relatively continuous micro-rough surface on the titanium foil, which improves the mechanical interlocking between titanium and the polyimide. The improved mechanical interlocking results in not only a stronger bond, but also a more durable bond, as the interface does not solely rely on chemical bonds that are susceptible to failure with water infiltration.

Cobb and Johnson [1] conducted research to optimize the interface, to be used in a second-generation, advanced HTCL. Titanium cracked lap shear (CLS) specimens were tested with combinations of two different polymeric resins with three different commercially available titanium surface treatments in a variety of exposure environments. Specifically, CLS specimens were constructed using the polyimides FM5 and LaRC-IAX to bond Ti-15-3 that had one of three commercially available surfaced treatments including: Pasa-Jell 107, Sol-Gel, and Turco 5578. These specimens were tested in constant amplitude fatigue and fracture toughness in one of three conditions: as received, after 5,000 hours at 177°C in dry air, and after 5,000 hours at 177°C in humidified air. The results showed the Ti-15-3/FM5/Ti-15-3 bond using Boeing's Sol-Gel surface treatment possessed superior fatigue durability in each environment over the other combinations. This work extends the previous research [1] to longer environmental exposures.

EXPERIMENTAL PROCEDURE

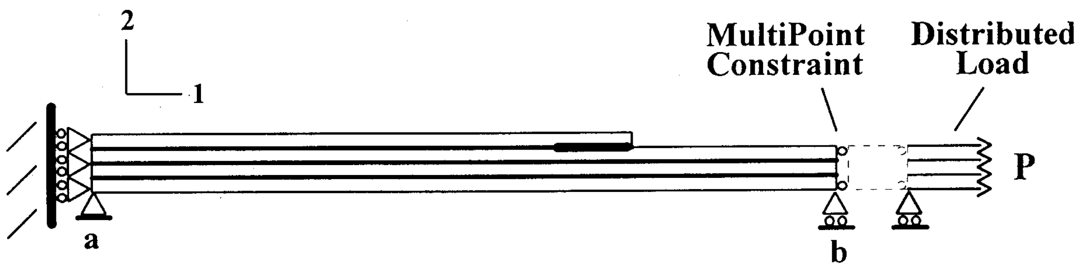

Figure 2. Cracked-Lap Shear Specimen

Panels were constructed using 50 mil thick sheets of Ti-15Al-3Cr-3Sn-3Al (Ti-15-3 – a metastable β-alloy) in the form of cracked lap shear specimens. As was used in Cobb's study, the three titanium surface treatments used were: Sol-Gel (Boeing), Turco 5578, and Pasa-Jell 107. The foils were then bonded together in the CLS specimens using either FM5 (Cytec Industries) or LaRC-IAX (NASA-LaRC) as the polymeric resin. The CLS specimen configuration was chosen due to its close approximation to the bonds commonly found in aerospace applications as well as the numerous studies that have demonstrated its viability for mixed-mode fracture. Each specimen was 0.5" wide with the "strap" portion being 6" long and the "lap" 4" long.

Specimens were exposed for 10,000 hours in either an arid (Hot-Dry) or humid (Hot-Wet) atmosphere, both at 177°C. They were subsequently tabbed and mechanically tested for fracture toughness and constant amplitude fatigue durability. A traveling microscope was used to determine and plot da/dN versus ΔG graphs.

RESULTS

The graphs in Figures 3 and 4 show that the FM5/Sol-Gel combination is the most durable in either the Hot-Dry or Hot-Wet environments. Additionally, data shows that while wet environment did greatly decrease the FM5/Sol-Gel or LaRC-IAX/Pasa-Jell bonds, a loss of durability was evidenced in the LaRC-IAX/Turco and LaRC-IAX/Sol-Gel combinations. The FM5/Pasa-Jell tests in the Hot-Dry and the FM5/Pasa-Jell and FM5/Turco tests in the Hot-Wet conditions either possessed little-to-no durability to graph or were not accomplished. However, as determined by Cobb [1] in previous research, both combinations proved to have more limited durability than FM5/Sol-Gel.

Figure 5 shows the FM5/Sol-Gel combination in all environments tested. The graph shows that the bond does weaken with greater exposure, however the humid environment has only an insignificant effect at either 5,000 hours or 10,000 hours exposure.

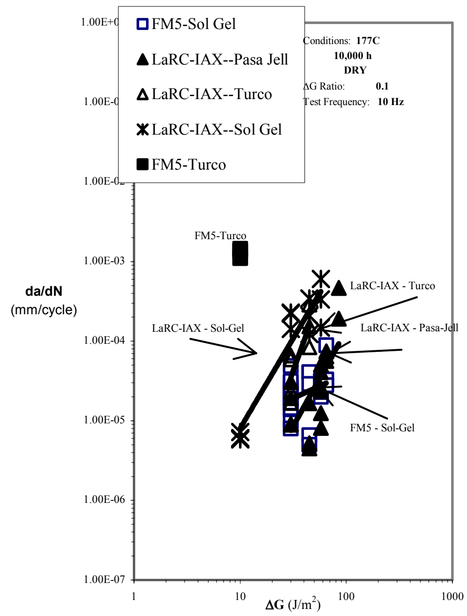

Figure 3. Mixed Mode Behavior of Ti-15-3 at 10,000 h Exposure in Dry, 177°C conditions.

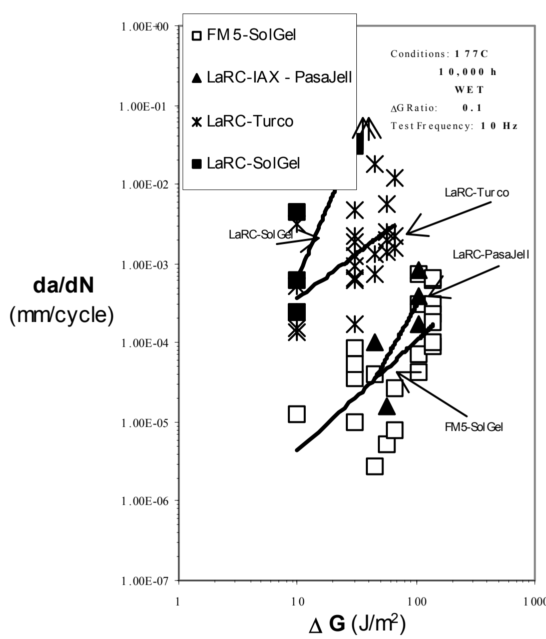

Figure 4. Mixed Mode Behavior of Ti-15-3 at 10,000 h Exposure in Humid, 177°C conditions.

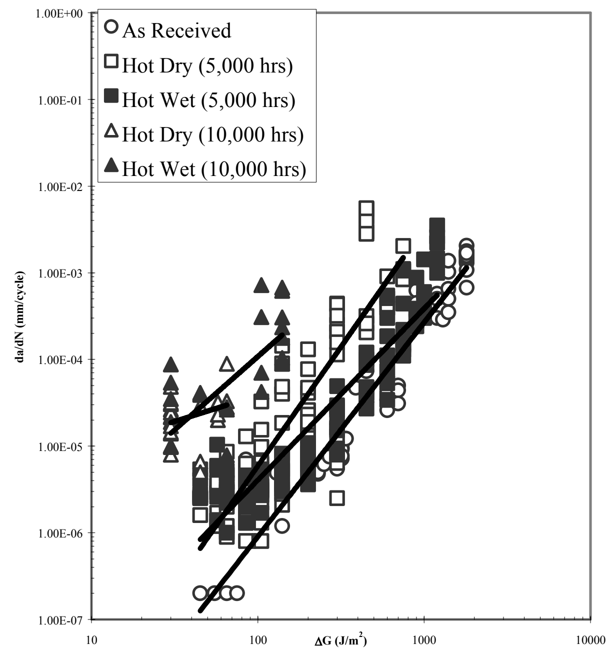

Figure 5. Mixed Mode Behavior of Ti-15-3/FM5-SolGel in all environments.

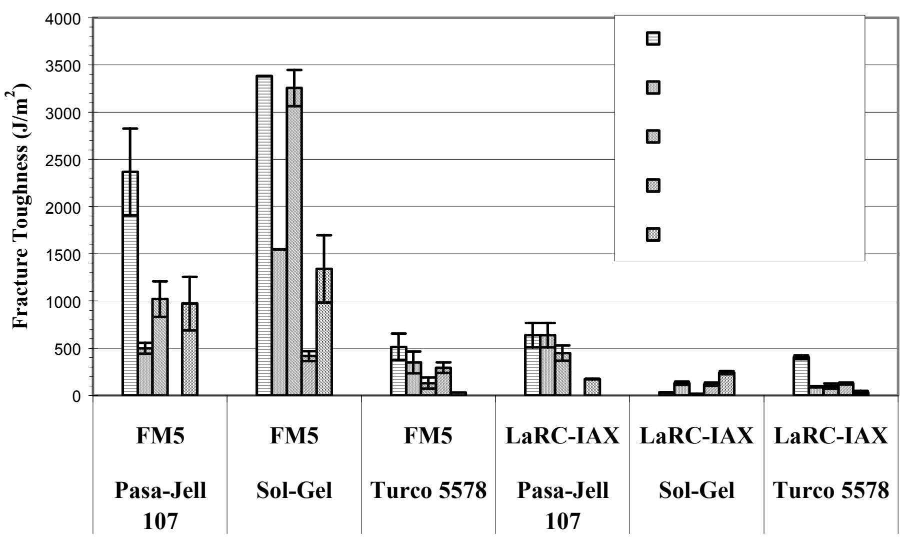

Figure 6. Fracture Toughness for all environments (95% confidence error bars shown)

Figure 6 depicts the fracture toughness properties of all combinations for all environments. Again, the FM5/Sol-Gel CLS surface proved the most durable for each exposure condition. Furthermore, after both 5,000 hours and 10,000 hours of exposure, the FM5/Sol-Gel actually possessed higher fracture toughness in the wet environment than the dry. This is probably due to a plasticization effect.

SUMMARY

Bonded titanium structure may offer several advantages, especially in elevated temperature applications. However, bond durability is a major concern. Several combinations of adhesive and surface treatment were evaluated in term of their fracture toughness and debonding resistance after exposure to 177°C. The FM5/Sol-Gel combination of polyimide and titanium surface treatment possesses the greatest fracture toughness and resistance to cyclic debond growth in both ambient and aggressive environments. Furthermore, in both 5,000 and 10,000 hours exposure time, the Hot/Wet environment produced a greater toughness in the FM5/Sol-Gel than the Hot/Dry condition.

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