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Effects of changes in temperature on fatigue crack growth of adhesively bonded Al 2080/SiC/20p-2080 Al laminated composites

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The effects of changes in test temperature from 25 to −125°C on the fatigue crack propagation of 2080/SiC/20p-2080 adhesive bonded laminates (ABL) with volume fraction ratio of 60/40 tested in the crack arrestor orientation were investigated. The fatigue behavior of the laminates was significantly different than that of the individual laminae as well as other types of laminates (i.e., diffusion bonded laminates). The fatigue crack growth behavior of the ABL's was significantly affected by the test temperature, particularly when the fatigue cracks approached and entered the adhesive layers. *In-situ* monitoring of fatigue crack growth and post mortem analyses were used to determine the likely source(s) of the effects of changes in test temperature and differences between the ABL and its constituents. © *2004 Kluwer Academic Publishers*

1. Introduction

One of the earliest composite materials, plywood, was used by ancient Egyptians [1]. A variety of composite materials (i.e., metal-matrix, ceramic-matrix, polymer-matrix) are now commonly used in various aircraft, rocket motor housings and missile casings, the automobile industry, etc. One of the more common metallic composites used in aerospace and aircraft applications are the discontinuously reinforced aluminum alloys (DRA). DRA materials are candidate materials for many applications due to their high specific stiffness and specific strength, although their damage tolerance is often not high enough to permit their more widespread use. The lamination of DRA with a material that has a high crack resistance, or the introduction of structural elements to retard crack growth, is one of the techniques being explored to improve the damage tolerance of these materials for use in a variety of industries.

Adhesive joining was an attractive joining technique because it saves weight up to 20% compared to conventional monolithic alloys [2], does not create stress concentrations, and generally produces longer fatigue life in comparison to laminate bonded using other techniques [3–5]. Early versions of mild steel laminates bonded with epoxy adhesives were made by Embury *et al.* [6]. In the late of 1970's, this was the basic idea for the fiber metal laminates (FML), ARALL Aramid Reinforced Aluminum Laminates and GLARE (Glass Reinforced), consisting of thin Al layers bonded together with adhesive layers containing long and strong fibers [3]. Fiber metal laminates originated from the 1950s at Fokker in the Netherlands, where a bonded laminate was found to successfully prevent rapid fatigue crack growth [7]. According to economical, safety, and technical feasibility, ARALL and GLARE are considered for applications such as aircraft lower wing skins, fuselage and tail members. One large scale application of fiber metal laminates is the entire top of the fuselage of Airbus A3XX [2, 7].

In all of these types of laminates, the adhesive layer itself was a composite material (i.e., graphite fibres reinforced epoxy, or Kevlar fibres reinforced epoxy). The focus of this investigation will be on laminaes bonded with epoxy only. The fatigue crack propagation behavior in the crack arrestor orientation has been evaluated over a range of temperatures relevant to a variety of potential applications.

2. Experimental procedures

2.1. Materials

Laminated metal composites were produced by Adhesive bonding of DRA layers and aluminum alloy layers using AF163-2K epoxy (3M Co) following the same techniques used by Osman *et al.* [8]. Both the

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TABLE I The layers thickness for ABL's

Laminate ID	Al layer thickness (mm)	DRA layer thickness (mm)
60/40 Thick	3.0	3.0
60/40 Thin	2.0	2.0

aluminum alloy and DRA layers had a 2080 matrix, with composition 4.1 Cu, 1.6 Mg, 0.02 Si, 0.2 Zn, balance Al. The DRA layers which contained 20 vol% SiC particles with average particle size 10–15 μm and the 2080 monolithic alloy were produced via powder metallurgy techniques followed by hot rolling to 2–3 mm thickness. Both materials were then heat treated to the peak aged (i.e., T6) condition using the following heat treatment: 500°C/4 h/WQ + 178°C/ 24 h/AC. The surfaces of each layer were then degreased and etched with nitric acid. ABR127 primer produced by American Cyanamid was then applied prior to application of an epoxy. The epoxy was cured in an autoclave at 120°C under 0.5 MPa pressure. The resulting laminates are designated 2080/SiC/20p-2080 ABL and contain a DRA/Al volume fraction ratio of 60/40. The volume fraction ratio listed indicates that 60% by volume of the laminate was DRA, while 40% was Al alloy. Table I indicates that laminates containing thick (i.e., 3 mm thickness) and thin (i.e., 2 mm thickness) layers were produced.

2.2. Specimen preparation

Fatigue crack propagation experiments on bend bars of the monolithic, DRA, and ABL's were conducted in general accordance with ASTM standard E647-2000 [9] and in general accordance with the British standard BS 6835-1 [10]. The adhesive bonded laminates (ABL's) were machined to dimensions using a grinding machine with a diamond wheel, since it was not possible to electro-discharge machine (EDM) machine through the non-conducting adhesive layers. General specimen dimensions for the laminates were in the range of W (width) = 10–15 mm, B (thickness) = 5–7 mm and S (span) = 40–60 mm. One of the specimens surfaces were ground through 400 SiC grit paper to be suitable for adhering a crack gage to monitor the crack growth, as discussed below. The other surface was polished to a mirror finish to enable visual crack monitoring and post mortem analysis. All specimens were tested in the crack arrestor direction, so that the crack growth occurred sequentially in the DRA and Al layers. The starter notch was placed using a diamond impregnated wire saw with wire diameter of 200 μm for all the ABL's, monolithic, and DRA materials in the manner used in our previous studies of diffusion bonded laminates [11, 12]. In the laminates, initial fatigue crack growth was always in the DRA layer. The specimen dimensions for the monolithic 2080 alloy were $W = 9$ mm, $B = 3$ mm and $S = 36$ mm, while for the 2080/SiC/20p DRA material were $W = 10$ mm, $B = 3$ mm and $S = 40$ mm.

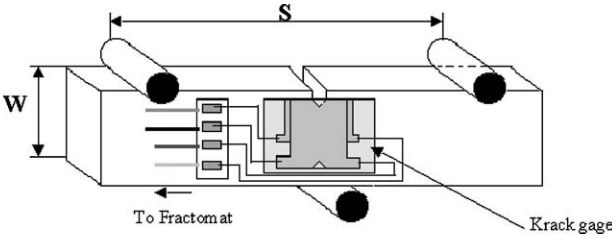

Figure 1 The position of the KRAK©-gage and the connections on a specimen prepared for fatigue crack growth test.

2.3. Fatigue testing

The fatigue tests were carried out on a 20 Kip MTS closed loop servohydraulic machine using a MTS 442 controller, and a Macintosh computer for data acquisition. All tests were performed under load control. Fatigue crack length was measured using 5 mm metallic foil KRAK© (KG-A05)-gages, monitored by a Fractomat model 1288 crack measurement system. One KRAK©-gage was bonded to one of the specimen surfaces with epoxy, and was connected to the Fractomat with the bondable terminals, Fig. 1. Measurements of the instantaneous crack length in each specimen was accomplished by monitoring the crack length of the KRAK©-gage bonded to the specimen surface. Visual observations confirmed that the crack length measured by the KRAK©-gage was very close to that exhibited on the polished surface. In practice, a fixed current is supplied to the KRAK©-gage and the voltage is measured across the gage. Crack growth in the specimen also cracks the gage, thereby creating a change in the voltage across the gage. The relationship between the crack length and the change in the voltage is linear, and provides a crack length resolution of 5.0 μm. The instantaneous crack length was used to control the fatigue test as well as monitor crack growth per cycle for the specimen as a whole, as well as within each individual layer. All specimens were fatigued at a frequency of 20 Hz using a sinusoidal wave form. A load ratio of either 0.1 or 0.3 was used presently.

Test temperatures selected for fatigue testing included room temperature, 0, −30, −45, −60 and −125°C. The low temperature tests were conducted using an insulated environmental chamber filled with liquid nitrogen (LN_2) vapors. The temperature was controlled to within ±1°C using a MTS 409.8 temperature controller. After achieving the test temperature inside the chamber, the specimens were held for about 30 min at this temperature before starting the test.

3. Fatigue results

3.1. Monolithic and DRA materials

The fatigue crack propagation behavior of the monolithic 2080 aluminum alloy is compared to the fatigue behavior of a 2080/SiC/20p DRA material, both tested in the T6 condition and at a load ratio (R) = 0.3 at room temperature in Fig. 2. The DRA material has a higher Paris law slope (2.9 vs. 2.4) than the monolithic material, and exhibits a higher fatigue threshold (3.5 MPa$\sqrt{}$m vs. 2.7 MPa$\sqrt{}$m) consistent with most reports comparing the fatigue behavior of monolithic aluminum alloys and DRA materials [13]. Previous studies on various monolithic 2xxx Al-alloys [14, 15] tested at low temperature revealed that decreasing the

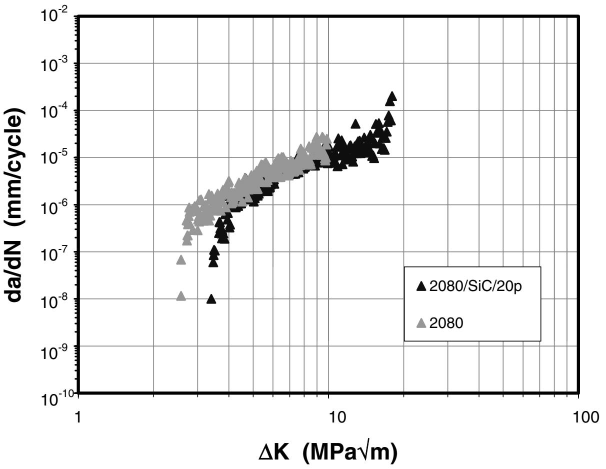

Figure 2 Fatigue crack propagation behavior for monolithic and DRA materials, tested at $R = 0.3$ at room temperature (*RT*).

temperature increases the fatigue threshold ΔK_{th}, while the Paris law slope, m, was not affected. Similar results were obtained on 6061/Al_2O_3/15p DRA and Be-Al composite materials [9, 16], but in these cases the Paris law slope increased with increasing T.

3.2. Adhesive bonded laminates

The fatigue crack growth behavior of the ABL's was significantly affected by the test temperature, particularly when the fatigue cracks approached and entered the adhesive layers. At test temperatures greater than −45°C, crack growth in the laminate was arrested by the adhesive layer as shown in Fig. 3. In these cases, crack bifurcation was exhibited in the adhesive, with subsequent growth along and within the adhesive layer occurring without any additional crack growth in the remaining DRA or Al alloy layers. In the fatigue crack growth curves this was accompanied by a significant drop in crack growth rate when the crack entered the adhesive layer, Fig. 4. Although tests at temperatures less than −45°C also exhibited initial crack arrest and reduction in crack growth rate at the DRA/adhesive or Al/adhesive layer, subsequent crack growth eventually occurred in the remaining layers, as shown in Fig. 5. In these cases, the initial fatigue crack arrest was not followed with crack growth along the adhesive interface. In contrast, subsequent fatigue crack initiation and growth occurred in the adjacent DRA or Al alloy layer, eventually producing catastrophic fracture of the ABL, Fig. 5. Similar observations were recorded for the effects of changes in that temperatures for both the thin and thick ABLs. Testing at temperature greater than approximately −45°C produced crack arrest and bifurcation in the adhesive layers without any further fatigue cracking in the remaining layers.

4. Discussion

The behavior of the monolithic and DRA materials tested presently are entirely consistent with previous work [13] and will not be discussed further. The behavior of ABL laminates are significantly different than that of diffusion bonded laminates reported elsewhere [11, 12]. In the present case, it is clear that the behavior of the adhesive interlayer exerts significant effects on the fatigue crack growth behavior when the fatigue crack enters the adhesive layers. At $T < -45°\text{C}$, crack growth is initially arrested by the adhesive, but continued fatigue cracking through the remaining layers occured. At $T > -45°\text{C}$, crack arrest and fatigue in the adhesive layer occurs along the adhesive/metal or DRA interface. This behavior roughly corresponds to the change in the mechanical properties of the AF 163-2K epoxy with changes in test temperature [17], Table II. The peel strength of AF 163-2K is significantly reduced at −55°C, indicating a ductile to brittle transition of the epoxy with decreasing test temperature. Separate studies of the interfacial strength of the Epoxy/Al and epoxy/DRA bonds have been conducted recently and reported elsewhere [18]. In these cases, the interface between the epoxy and the layers was separated in shear using a 20 Kip MTS servohydraulic testing machine. Tests were conducted at temperatures above and below −45°C. The interface strength was shown to be temperature dependent, with embrittlement at the lowest test temperatures, consistent with the data reported in Table II. The brittle behavior of the epoxy at

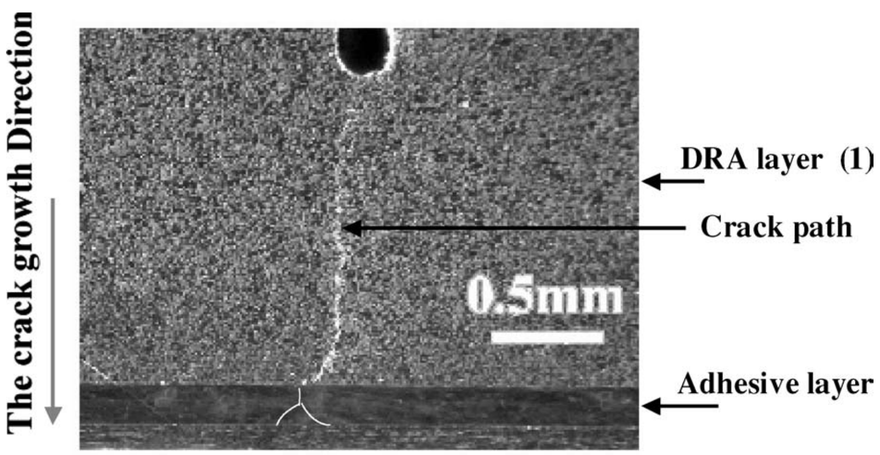

Figure 3 The crack growth behavior in (2080/SiC/20p-2080) with a vol. Fraction ratio [DRA/Al-alloy] of 60/40 thick layers laminate tested in fatigue at $T = -30°\text{C}$ and $R = 0.1$.

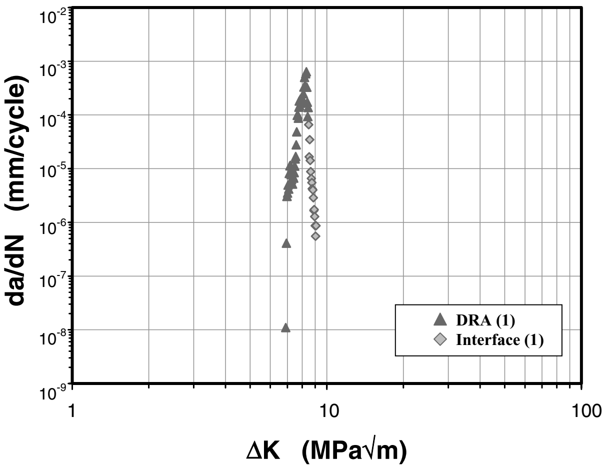

Figure 4 The crack growth behavior and the crack path in (2080/SiC/20p-2080) ABL with a DRA/Al volume fraction ratio of 57/43 thick tested in fatigue at $R = 0.3$, at $T = -30°\text{C}$. A significant reduction in crack velocity is obtained when the fatigue crack reaches the interface.

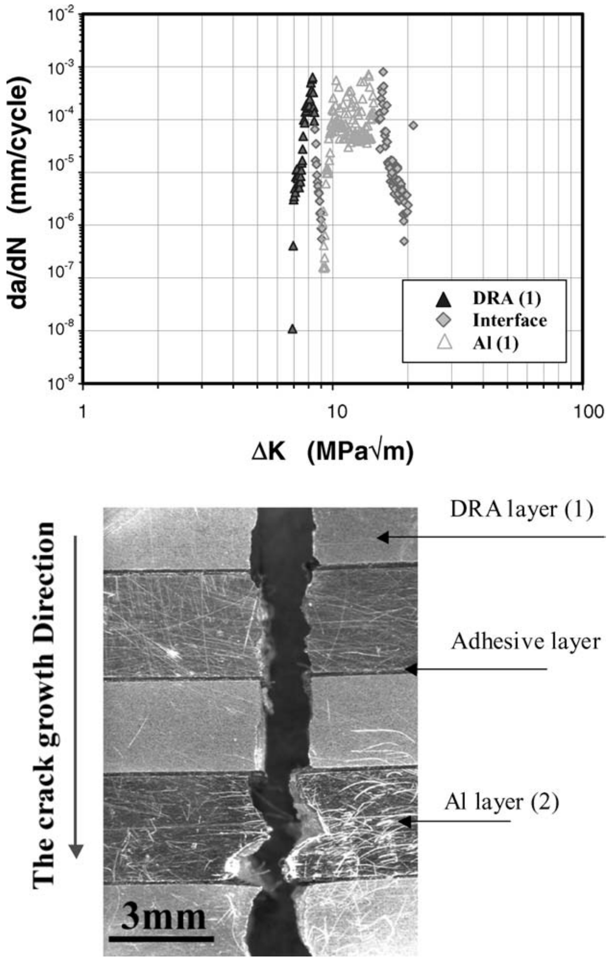

Figure 5 The crack growth behavior and the crack path in (2080/SiC/20p-2080) ABL with a DRA/Al volume fraction ratio of 57/43 thick tested in fatigue at $R = 0.3$ at $T = -60°\text{C}$. Abrupt changes in crack velocity are obtained at the adhesive interfaces, with subsequent fatigue crack growth in the remaining Al and DRA layers.

$T < -45°\text{C}$ apparently enables initial arrest of the crack with subsequent fatigue of the epoxy interlayer and subsequent fatigue of the remaining layers. The tougher behavior of the epoxy at $T > -45°\text{C}$ promotes fatigue crack bifurcation along the interface.

TABLE II The mechanical properties of AF 163-2K epoxy [17]

Temperature (°C)	σ_y (MPa)	E (GPa)	G (GPa)	Peel strength (MPa)
−55	75	1.6	6.2	25
24	49	1.1	5.8	44
82	–	–	–	40

T_g (dry) = 108°C.
T_g (wet) = 82°C.
CTE (−30°C: 50°C) = $90 * 10^{-6}$.

5. Conclusions

1. Fatigue thresholds and Paris law slopes of monolithic 2080 and DRA were measured and found consistent with previous research. In particular, the DRA had a higher fatigue threshold and Paris law slope than the monolithic 2080.
2. Fatigue behavior of the ABL laminates was dependent on test temperature. Crack arrest and bifurcation along the Al/adhesive and DRA/adhesive interface was observed at $T > -45°\text{C}$. Tests at $T < -45°\text{C}$ similarly showed crack arrest at the adhesive, but continued fatigue crack propagation occurred through the remaining layer.
3. The difference in behavior of the adhesive was related to the known effects of changes in test temperature on the peel strength and energy absorbing capability of the adhesive.

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