Development and characterization of fatigue resistant Aramid reinforced aluminium laminates (ARALL) for fatigue Critical aircraft components

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Abstract. The structural weight of an aircraft has always been a controlling parameter that governs its fuel efficiency and transport capacity. In pursuit of achieving light-weight aircraft structures, high design stress levels have to be adopted and materials with high specific strength such as Aluminum etc. are to be deployed. However, an extensive spectrum of fatigue load exists at the aircraft wings and other aerodynamic components that may cause initiation and propagation of fatigue cracks and concludes in a catastrophic rupture. Fatigue is therefore the limiting design parameter in such cases and materials with high fatigue resistance are then required. A major improvement in the fatigue behavior was observed by laminating Kevlar fibers with Aluminum using epoxy. ARALL (Aramid Reinforced ALuminum Laminates) is a fatigue resistant hybrid composite that consists of layers of thin high strength aluminum alloy sheets surface bonded with aramid fibers. The intact aramid fibers tie up the fatigue cracks, thus reducing the stress intensity factor at the crack tip as a result of which the fatigue properties of can be enhanced with orders of magnitude as compared to monolithic high strength Aluminum alloy sheets. Significant amount of weight savings can be achieved in fatigue critical components in comparison with the traditional materials used in aircraft.

1. Introduction
The structural components of an aircraft endure severe cyclic loads during their service life. Some of the stress critical zones may develop a growing crack that propagates with each stress reversal cycle. In such cases, even a minor crack has a very sharp radius at tip and the corresponding stress intensity factor is very high. This results in a rapidly expanding crack that terminates in a catastrophic rupture and hence fatigue resistant materials are highly looked-for in order to prolong the service life of the component. The desired features of the materials for aircraft structures include its low weight, damage tolerance and resilience against the rigorous environmental factors. High strength aluminum alloys are considered as the eligible material for the aircraft structures as they meet the demanding set of properties required in aerospace materials [1].

A relatively new class of composite materials is Fiber Metal Laminates (FML) that are light in weight as well as damage tolerant against fatigue loads. Alternate layers of fibers and metal sheets bonded together via resin impregnation produce a component with comparatively low density, high specific strength and the desired Fatigue tolerance [2].
In 1983, the Delft University of Technology developed a new composite material called ARALL (Aramid Reinforced Aluminum Laminate) [2] which is a laminated structure containing alternating of thin sheets of Aluminum based alloys and Kevlar impregnated with epoxy [2]. The presence of Kevlar significantly reduced the weight and imparted the fatigue tolerance in the structure [3]. Further studies were made in 1984 the durability of ARALL was figured out against the environmental factors [4]. Gunnink et al. analyzed the aerospace structural designs made out of these laminates in 1987 [5] while the damage tolerance of ARALL in fuselage skin was examined in 1989 [6]. The fatigue behavior was reported along with the different laminate orientation with respect to the applied loading direction in 1995 [7]. In 2011, Sham Rasad et. al. tested ARALL for the interlaminar & intralaminar strength of the interfaces [8]. These interfacial strengths affects directly on the performance of the material and are desired to be controlled.

The current research work is related with the fabrication of these Aramid reinforced Aluminum laminates by sandwiching Kevlar fiber between two Aluminum sheets. Anodizing the aluminum sheet prior to VARTM process is a must in order to improve the adhesive bonding between two materials that belong to dissimilar classes.

2. Experimental Work

2.1. Fabrication of ARALL

For the fabrication of these laminates, three different materials are utilized:
- Aluminum 2024 T3 alclad
- Kevlar 49 Fibre Cloth
- Araldite LY 5052 Epoxy

The major concern in the fabrication of these laminates is the adhesion of Kevlar-49 and Aluminum-2024. Interfaces are the weak links in such kind of materials, and it is desired to alter the surface properties of the aluminum sheets for greater surface area and a stronger adhesion [9]. One way is to create micro scale pores on the surface of mechanically cleaned Aluminum via a process called Anodizing. Such metal surface modification process includes mechanical cleaning, chemical cleaning and electrochemical anodizing.

Although solvent degreasing is carried out to degrease the surface and to remove the contaminants but alone it is not sufficient to improve the bond durability for longer period [10]. Mechanical methods of abrasion are used [11] in order to remove Al₂O₃ layer and to create micro roughness on the metal surface, leaving it more adherent to the other surface. The surface topology can be altered through abrasion of the surface using sand paper and hence the wet-ability of surface can be increased [12]. The processes of alkaline cleaning and acid etching are then carried out to remove the debris and to dissolve the oxide layer. Anodizing is performed on these surfaces which creates a porous oxide layer on the surface of the metal. This layer is highly rough and contains micro pores which ensure the permanent bond between metal and the fiber [10].

![Figure 1. Setup for Aluminum Anodizing Process](image-url)
Multiple sets of Aluminum 2024 sheet of 0.5mm thickness were cut in the size of 150mm x 80mm and were grinded using 1200C fine emery paper to attain a uniform surface. The sheets were alkaline cleaned using the NaOH solution (12g/liter) and acid etched in a solution containing 10wt% sodium dichromate, 30wt% sulphuric acid and 60wt% distilled water held at 80°C using hotplate and magnetic stirrer. To validate whether the degreasing is achieved fully or not, water break test was done at each stage of cleaning.

Anodizing was then carried out on the mechanically cleaned acid etched sheets in 12wt% phosphoric acid (H₃PO₄) bath held at ambient temperature. Stainless steel sheet was used as cathode and the Aluminum sheet was made anode while a voltage of 15V±0.1V was maintained for 25 min (figure 1). Optical imagery of the anodized surface of Aluminum at a magnification of 600x is shown in figure 3.

Following Anodizing, the Aluminum sheets were laminated with Kevlar via the process of Vacuum Assisted Resin Transfer Molding (VARTM). To serve as a mold base, acetone cleaned glass slab was used with mold release wax applied on its surface. Aluminum and Kevlar were arranged in 2:1 configuration and the auxiliaries of the process such as peel plys and resin transfer mesh were placed in accordance with the standard VARTM procedure. The VARTM setup is illustrated in figure 2. Vacuum was created by applying pressure bags and vacuum suction pump and resin (Araldite LY 5052) was infused into the mold which spread due to the capillary action. After primary gelation time, samples was extracted from the fabrication panel and post cured at 100°C for 4 hrs.

2.2. Fatigue Testing
The post cured samples were cut in dimensions of 135mm x 25mm using MetaCut M250. Bending Fatigue testing was performed on the samples keeping a displacement rate of 50mm per minute and a stress level of 80% of the yield stress of ARALL. A stress reversal of 50 cycles was applied and the corresponding behavior of flexural stress-strain was plotted.

3. Results and Discussion
A marked difference in surface morphology of Anodized Aluminum alloy was observed when examined under Metkon Metallurgical Microscope. The observed microstructure taken at 600x magnification is depicted in figure 3. The presence of porous oxide layer improves its adherence with Kevlar since the infiltration of epoxy becomes easy.
Figure 3. Optical micrograph of a) mechanically cleaned Aluminum b) anodized Aluminum surface showing porous oxide layer

Figure 4 illustrates the bending fatigue cycles of ARALL given at a displacement rate of 50mm per minutes. The sample was tested at stress levels ranging from a maximum value of 205 MPa to a minimum of 40 MPa. Even at such level of stress range and the applied strain rate, no visible drop in stress value was observed after 50 cycles. No visible signs of interfacial disbondment were observed on the sample after testing.

When this data was plotted for flexural stress vs. flexural strain, the corresponding stress reversal cycles were attained as shown in figure 5. Initially, before the first cycle, the straight line proportionality was observed till the maximum applied stress (80% of the yield stress) was reached. When the load decreased to its lower value, the curve didn’t adopted the same track, rather it formed in a closed loop for the given number of cycles. The material kept its elastic modulus to a constant value throughout the stress reversal cycles as elucidated from slope of the curve.
4. Conclusion and Future Work
For sufficient weight savings that is a main concern in the case of aerospace industry, aramid reinforced Aluminum laminates can serve as a structural material with high damage tolerance. If the process of Aluminum anodization is well optimized, a strong interface can be achieved via infiltration of epoxy into the porous Al₂O₃ layer that has been developed intentionally. A strong interface of ARALL promoted resistance to stress reversal cycles and bending fatigue loads in comparison with monolithic materials out of which ARALL is fabricated. Moreover, between the two of these anodized Aluminum layers, woven Kevlar 49 fibers hinder any crack propagation due to ‘crack arrest’ mechanism. Tests to measure the Interlaminar Shear Strength and Tee Peel resistance [13] can assess the bonding strength and interfacial adhesion and will be conducted in future.

5. References
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