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Mechanical characterization of fiber metal laminate based on aramid fiber reinforced polypropylene

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ABSTRACT

In this paper, the tensile properties of fiber-metal laminates (FMLs) made of a low-ductility aluminum alloy and aramid fabric/polypropylene matrix composite are evaluated. The tensile testing results show that the FMLs exhibit a more ductile behavior than that of their constituents, indicated by the increased strain to failure. The excellent adhesion between FML constituents, as confirmed by single lap joint shear test and optical microscopy, enabled a more globalized plastic deformation in the aluminum sheet of the FML leading to an increase of strain to failure, which offers an advantage in engineering structural applications where large deformations are present and strain to failure is more important than strength. The findings in this study are important from a design viewpoint of FMLs because the results show that FMLs properties, such as toughness and strain to failure, can potentially be tailored to absorb energy at different rates.

1. Introduction

The demand for fatigue-resistant materials aligned with the damage tolerant design philosophy as outlined by the Federal Aviation Administration [1] have led to the need to develop tough materials with high damage tolerance [2]. Lightweight materials such as fiber-reinforced polymer (FRP) materials and aluminum alloys have been extensively used in aeronautical applications; however, the drawbacks of these systems are that FRPs are susceptible to impact damage while aluminum alloys are susceptible to fatigue crack growth [2]. To overcome these drawbacks, materials that combine the advantages of both aluminum alloys and FRPs have been developed [3], such as fiber metal laminates (FMLs). FMLs, which are structural hybrid composite materials based on thin sheets of metal alloys and layers of FRP materials [4,5], are an excellent example of combining the mechanical properties of their constituents to produce an improved material behavior. FMLs have been successfully used in the aeronautical industry [1,4,6]. Metal sheets in FMLs are usually aluminum alloy; however, FMLs based on magnesium alloy [7] and titanium [8,9] have also been developed.

FMLs exhibit an outstanding mechanical performance, which is the result of the combination of the excellent fatigue resistance and high strength of FRP composites with the ductility of metal alloys [10]. FMLs have shown better performance under impact [11,12] and fatigue in comparison with monolithic aluminum [3]. Moreover, they are lightweight and have high energy absorbing capacity. However, the greatest disadvantage of FMLs that are based on epoxy matrix is the long processing cycle to cure the matrix for the FRP layer [8]. This problem increases production time and reduces productivity, which leads to an increase in the global cost of FMLs manufacturing [4]. Some other disadvantages of thermosetting based FMLs are the low interlaminar fracture toughness and the difficulties associated with repair [13]. In contrast, it has been shown that the associated manufacturing costs of FMLs can be reduced when thermoplastic matrix is employed [8]. It has been shown that thermoplastic based magnesium alloy FMLs [7] have excellent energy-absorbing properties when compared to thermoset-based aluminum alloy FMLs. Additionally, environmental awareness is forcing the composites industry to produce environmentally friendly materials [14], and thus, topics like material disposal or recycling of composite materials cannot be ignored, even though this imply a serious challenge for the industry to maintain low-cost production and performance [15]. Therefore, FMLs based on thermoplastic composite layers offer environmental advantages such as recyclability, post-forming and potentially rapid processing making them a better option against thermoset-based composite FMLs [16] when environmental issues are important.

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Several studies have been conducted on the properties of thermoplastic based FMLs. Carrillo and Cantwell investigated the impact and tensile properties of FMLs based on a composite with polypropylene (PP) matrix reinforced with PP fiber [3], which is known as self-reinforced polypropylene (SRPP). They found that these materials exhibited higher tensile strength than that of plain thermoplastic composite and strain to failure greater than that measured on plain aluminum alloy. Abdullah and Cantwell [17] studied the high velocity impact resistance of FMLs based on SRPP and found that the perforation resistance of this material was superior to that of a composite material made from glass fiber with phenolic matrix. Kuan et al. [18] studied environmental-friendly FMLs, which included FMLs based on SRPP and FMLs based on a composite material made with PP matrix reinforced with natural fibers. They found that the SRPP based FMLs exhibited the highest impact resistance.

PP matrix has also been used as the matrix of composite materials reinforced with high-performance fibers such as aramid fibers [19], which have high tensile strength, high elastic modulus and high tenacity [19]. Although thermoset-based FMLs reinforced with aramid fiber has been extensively investigated [4,20], thermoplastic-based FMLs reinforced with aramid fiber have been scarcely studied [21].

This study is motivated by the lack of knowledge in the study of thermoplastic-based FMLs with aramid fiber composite. In this work, FMLs with a core made of an aramid fabric/PP matrix composite and two outer layers of an aluminum alloy are investigated. This research work focuses on the characterization of the tensile mechanical properties of the FML and its constituents. The deformation mechanisms of the FML are discussed and analyzed by optical microscopy. Materials and experimental procedures are described in Section 2. Results and discussion are presented in Section 3, followed by conclusions in Section 4.

2. Materials and methods

2.1. Materials

The thermoplastic matrix employed in this study is the commercially available polypropylene (PP) adhesive film Collano 23.110 (Collano Adhesives, Switzerland). The mechanical properties of the PP adhesive reported by the manufacturer are: density of 910 kg/m^3, elastic modulus of 870 MPa, yield strength of 17.2 MPa and ultimate strain of 1050% [22]. Twenty layers of PP film, each one with an average thickness of 0.1 mm, were used to machine tensile specimens with a gage length of 25.4 mm and a thickness of 1.5 mm. The specimens were used to obtain tensile mechanical properties in accordance ASTM D 638 standard using a universal testing machine equipped with a load cell of 0.5 kN and a Shimadzu SG-25-10 extensometer. The tensile test was performed at a crosshead speed of 50 mm/min.

An 1100-H14 aluminum alloy sheet (Nacobre, Mexico) with a thickness of 0.3 mm was used in this study for the fabrication of FMLs. This aluminum was selected because of its low cost when compared to aerospace grade aluminum alloys and to investigate the improvement of the performance of a low-ductility aluminum through constituent's consolidation of the FML. The mechanical properties of the 1100-H14 aluminum alloy reported by the manufacturer are yield strength of 95.16 MPa, maximum strength in the range of 109.9–145.2 MPa and failure strain of 1–2% [23]. The density of 1100-H14 aluminum alloy has been reported as 2712.6 kg/m^3 [24]. Tensile properties of 1100-H14 aluminum alloy sheet were measured using a specimen with a gage length of 120 mm in accordance to ASTM D 3039 standard using a universal testing machine with a load cell of 5 kN and a crosshead speed of 2 mm/min.

A plain-woven aramid fabric (style 724, Kevlar 129 fiber, 1000 denier) was used as reinforcement material for the laminates. The tensile properties of the fabric were measured according to ASTM D 5035 using the ravel strip method, which requires at least 20 yarns across the width of the specimen [25]. Tests were performed in a universal testing machine with a crosshead displacement rate of 300 mm/min.

2.2. Surface treatment of single fiber

With the aim to improve fiber-matrix adhesion, a chemical surface treatment was applied to the fiber surface. For this, single Kevlar fibers were extracted carefully from the fabric and subjected to Soxhlet extraction of sizing using acetone [26]. Subsequently, the fiber was immersed in a 40 wt% phosphoric acid (H_3PO_4) solution followed by a rinse stage [27].

2.3. Infrared spectroscopy

Infrared (IR) spectroscopy was used to identify the difference in the chemical composition of both treated and untreated single fibers, and PP matrix. A Nicolet Protege 460 spectrophotometer was used to obtain the IR spectra. Pastille samples for the spectrophotometer were prepared using the pressed disk method. Pastilles were fabricated by grinding up either fibers or PP matrix and mixing them with potassium bromide (KBr).

2.4. Microbond pull-out test

Fiber-matrix interface strength was measured using the microbond pull-out test [28,29]. Tests were carried out on microbond specimens with treated and untreated Kevlar single fibers. To fabricate the specimens, single Kevlar fibers were placed on a metallic frame and impregnated with matrix powder (Fig. 1a). Subsequently, the frame was placed into an oven at 175 °C for 120 min allowing the matrix powder to melt around the fiber and form droplets with diameter in the range of 120–190 μm as observed in an optical microscope (Fig. 1b). The interfacial shear strength was measured using the microbond pull-out test using a universal testing machine with a 50-g load cell at a crosshead speed of 0.1 mm/min. The test consists of pulling a fiber end while the droplet is held by the microvice jaws as shown in Fig. 1c. At least 13 samples were measured for each type of fiber. The interfacial shear strength τ, was calculated as $\tau = F/\pi DL$ [30,31], where F is the pull-out force, L is the embedded length of the fiber and D is the droplet diameter.

2.5. Fabrication of FML and composite specimens and mechanical testing

FMLs were fabricated using the stacking sequence of constituents shown in Fig. 2a. The constituents were two aluminum sheets with a thickness of 0.3 mm, two layers of PP film with a thickness 0.1 mm each and one layer of aramid woven fabric. The FMLs panels were thermo-molded using a Carver hot press (Model Auto Series) at 175 °C with a pressure of 2 MPa for 20 min; FMLs constituents were consolidated in a single stage. Composite specimens (without the aluminum outer faces) were fabricated using the same process used for the FMLs. Both FMLs and composite samples are made with the woven fabric in the 0°/90° lay-up. For the composites, the volume fraction of the fiber was 40% fiber, whereas for the FMLs the volume fraction of the aluminum was 62.4%. The geometry of both composite laminate and FML test specimens was established in accordance with the ASTM 3039 standard as shown in Fig. 2b. The tensile test performed on FML test specimens and constituent materials was carried out in two lots of 5 samples each, using a universal testing machine with a