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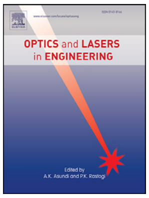

Laser forming of glass laminate aluminium reinforced epoxy (GLARE): On the role of mechanical, physical and chemical interactions in the multi-layers material

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ABSTRACT

The present work concerns the laser forming of Fiber-Metal Laminates (FMLs) by a high power diode laser source. FMLs are made of different layers of metal and composite material. The wide difference in the thermo-mechanical and physical properties of the different layers within FMLs makes them extremely problematic to be reprocessed. In particular, the economic shaping of FMLs in complex shapes is practically impossible, limiting greatly their field of application. Therefore, this manuscript explores the possibility of using laser forming to reprocess FMLs and obtain final components with precisely controlled bending radii. For this purpose, the effect of the laser operating parameters, namely laser power, scanning speed and number of passes, on the final shapes of FMLs was investigated. Secondly, further tests were also performed to obtain other complex shapes on FMLs from multiple laser scanning paths, side by side and equidistant on the substrates. An analysis of the failure of the substrates during the shaping process was also performed, with particular emphasis on deformation mechanisms, interfacial delamination and thermal alteration of the layers. The experimental results showed the good viability of laser reprocessing to shape FMLs, thus opening up new possible applications of this class of materials in aeronautical and aerospace applications.

1. Introduction

Fiber-metal laminates (FMLs) are an innovative class of high-performance composite materials that are of great interest to the aeronautic and aerospace industry segments [1–6]. These materials are composed of superimposed layers, a fiber-reinforced polymer matrix composite [6] (commonly, thermosetting) glued with an extremely thin sheet of metallic material. The main feature of the FMLs is the ability to combine the typical toughness and fatigue strength of the metal, with the lightness, chemical inertness and high specific mechanical strength of the composite materials [5–9]. Therefore, FMLs are ideal candidates for replacing aluminium and magnesium alloys in various industrial applications [6]. GLARE (Glass Laminate Aluminium Reinforced Epoxy) is a class of FMLs of particular interest. Around 500 m^2 GLARE are used in the manufacturing process of each Airbus A380. GLARE is a material composed of alternating layers of thin metal foils and prepregs. The prepregs are made of glass fibers and epoxy resin. The prepregs have the function of gluing the different sheets of metal [10,11]. The adhesive strength of prepregs is very high, thus allowing the manufacturing of FML with several layers of fibers that are oriented differently so as to manufacture laminates with better performance, also capable of withstanding bidirectional loads [7–10].

The current industrial diffusion of FMLs is, however, hampered by two factors: a high purchase cost and the limited processability of the material. In particular, shaping/forming of FMLs can be extremely costly, often requiring specific equipment that is difficult to amortise on the production batch [11].

Nowadays, the main techniques involved in the shaping/forming of FMLs are artisanal. These techniques are strongly linked to the ability of the operators who shape, by simple manual deposition on a mold, individual layers of laminates until they reach the desired shapes by layer superimposition. A curing process in a high temperature and pressure furnace follows manual deposition of the laminates [12–14]. The costs related to the purchase of the raw materials and those related to the complex manufacturing operations often discourage the use of FMLs. Nevertheless, these classes of materials, being mainly made of metal, can show, during the forming/shaping processes, responses very similar to those of metals [15,16]. Therefore, starting from flat laminates, it is possible to adopt non-conventional shaping techniques that are not based on molds to obtain profiles and shapes of practical interest [16–19].

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In this regard, the present work deals with the shaping of FMLs, in particular of GLAREs, through an easy and versatile approach involving a laser source to process the laminates without molds. In particular, this work evaluates the possibility of shaping prototypal laminates by means of progressive (constant step) bending (i.e., multiple laser scanning paths placed side by side and equidistant on the substrate surface) to arrive at a final shape characterised by multiple curvature and high precision, suitable for specific needs such as aircraft fuselages manufacturing.

2. Experimental

2.1. Materials

In the present work, two different types of Fiber Metal Laminates (FLMs) were used. The first material is denominated GLARE1. It consists of two layers of aluminium alloys AA7475-T671 and an intermediate layer of composite material. The composite material (i.e., a prepreg) is, in turn, composed of a thermosetting matrix (i.e., an epoxy resin, type FM906) reinforced with glass fiber. The second material is denominated GLARE2. It is composed of three layers of aluminium alloys AA2024-T3, interposed with two layers of composite material. The composite material consists of a thermosetting matrix (i.e., an epoxy resin, type FM94) reinforced with glass fiber. A $1000 \times 1500 \times 1$ mm^3 sheet of GLARE1 was cut, under temperature control, by a diamond blade in 50×70 mm^2 substrates. A $1000 \times 1500 \times 2$ mm^3 sheet of GLARE2 was cut, under temperature control, by a diamond blade in 50×70 mm^2 substrates. Both laminates were kindly provided by GTM Advanced Structures (GTM-AS, The Hague, The Netherlands), an independent R&D organization dedicated to the development, production and testing of advanced hybrid materials and structures (metals, hybrids, like GLARE and other composite materials) for aerospace applications.

The techniques for producing FLMs are proprietary. However, the production process starts from an aluminum foil, previously *activated* by pre-treating it in a caustic bath (NaOH in water). The pre-treatment generates hydroxyl groups (-OH) on the metal surface. The pre-treated aluminium is then coated with a silane-based primer. The silane, which is commonly used, is the 3-glycidyloxypropyltrimethoxysilane. This silane has three Si-O-R groups (with $-R = -CH_3$) and an epoxy group. The Si-O-R groups can react by hydrolysis and condensation with the hydroxyls on the surface of the aluminium sheets, forming strong covalent bonds (i.e., the silanols, Si-OH) and evacuating alcohol. Aluminium is bonded to prepregs by applying heat and pressure. During this phase, the epoxy group on silane molecules may also react with the epoxy resin in the prepregs. In fact, the epoxy resin inside the prepregs is commonly a two-pack resin with an amine hardener, which can easily react with the epoxy group of the 3-glycidyloxypropyltrimethoxysilane. In this way, a covalent bond is generated between the primer on the surface of the aluminium layer and the prepreg. The technique for producing GLARE and, in particular, the number of layers therein, significantly influences the laminate response during the laser forming process.

2.2. Laser source

Laser forming of the laminates was performed by a high power diode laser (Rofin Sinar, DL015). The laser source operates with a wavelength of 940 nm and an elliptic spot with two half-axes of 0.6 and 1.9 mm, respectively. The maximum power of the laser is 1500 W, although the maximum power used during the experimental campaign was 250 W. The laser beam was focused by a short focal lens of 63 mm, the best solution when the thickness of the material to process is small. The movement of the substrates was ensured by a CNC system, synchronised with the laser system. The triggering of the laser source, the movement of the substrates and the setting of the laser operational parameters were entered by a front panel and controlled through a dedicated software developed in Labview.

Table 1
First experimental campaign on FMLs by high power diode laser (two replications for each test): (a) single bend on GLARE1; (b) single bend on GLARE2.

1st Step		
Experimental plan on GLARE1		
Power (W)	Scan speed (mm/s)	N° of passes
145	10	3
185	15	6
225	20	–
1st Step		
Experimental plan on GLARE2		
Power (W)	Scan speed (mm/s)	N° of passes
125	10	3
150	20	6
175	–	–

2.3. Laser forming

The experimental campaign involved two successive steps:

- The first step in which a single bending was performed on each substrate to understand the interaction of the laser source with the two materials, GLARE1 and GLARE2, and identify the correct choice of the operating parameters (Fig. 1a, b, c).
- The second step in which, once the best operating parameters for each material have been identified, a sequence of laser passes, placed side by side and equidistant on the surface of the substrate, was performed to obtain a curve profile with a precise curvature radii from a flat laminate (Fig. 1a, b, d).

The experimental tests were always performed using the orthogonal scanning direction to the direction of lamination of the aluminium layer in the GLAREs so as to exploit the anisotropy of the material. Nitrogen gas was coaxially fluxed to the laser beam on the substrate during laser scanning for oxidation protection. The choice of nitrogen as protection gas was due to the lower cost and greater thermal capacity than argon. Lastly, during laser irradiation, the observed bending mechanism of the substrates was always the Thermal Gradient Mechanism (TGM) in agreement with [20]. Accordingly, the thermal gradient caused the substrate to bend in the direction of the surface directly exposed to the laser beam, regardless of the setting of the operating parameters.

2.3.1. First experimental set

During the first step of the experimental campaign, the laser beam was irradiated along a linear pattern located exactly at the middle of the substrate and directed orthogonally to the larger side (70 mm) of the substrate (Fig. 1a). The laser spot is advanced orthogonally to the largest half-axis (1.9 mm). In this way, the laser energy was delivered on a wider band of the substrate (1.9 mm × 50 mm), thus generating a uniform and less concentrated distribution of irradiation, thus reducing the occurrence of thermal degradation of the polymeric matrix. A K-type thermocouple (Chromel-Alumel) was placed on top of the substrate to measure the temperature reached during the forming process. The thermocouple was connected to a multimeter that allowed to store the temperature every second (1 Hz) during the laser forming process. Table 1 summarises the experimental plan for the two different materials. Each experimental campaign consisted of 36 tests for GLARE1 and 24 tests for GLARE2, combining all experimental factors and levels. The temperature and bending angles were the result of the first experimental campaign. The measurement of the bending angle of the substrates was performed using a profile projector (Mitutoyo, A-3000), with an error of