A review: Fibre metal laminates, background, bonding types and applied test methods

Tamer Sinmazçelik \textsuperscript{a,b,*}, Egemen Avcu \textsuperscript{a}, Mustafa Özgür Bora \textsuperscript{a}, Onur Çoban \textsuperscript{a}

\textsuperscript{a} Kocaeli University, Mech. Eng. Dept., Umuttepe Campus, 41380 Izmit, Kocaeli, Turkey
\textsuperscript{b} TUBITAK-MRC, Materials Institute, P.K. 21, 41470 Gebze, Kocaeli, Turkey

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\textbf{A B S T R A C T}

During the past decades, increasing demand in aircraft industry for high-performance, lightweight structures have stimulated a strong trend towards the development of refined models for fibre-metal laminates (FMLs). Fibre metal laminates are hybrid composite materials built up from interlacing layers of thin metals and fibre reinforced adhesives. The most commercially available fibre metal laminates (FMLs) are ARALL (Aramid Reinforced Aluminium Laminate), based on aramid fibres, GLARE (Glass Reinforced Aluminium Laminate), based on high strength glass fibres and CARALL (Carbon Reinforced Aluminium Laminate), based on carbon fibres. Taking advantage of the hybrid nature from their two key constituents: metals (mostly aluminium) and fibre-reinforced laminate, these composites offer several advantages such as better damage tolerance to fatigue crack growth and impact damage especially for aircraft applications. Metallic layers and fibre reinforced laminate can be bonded by classical techniques, i.e. mechanically and adhesively. Adhesively bonded fibre metal laminates have been shown to be far more fatigue resistant than equivalent mechanically bonded structures.

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1. Introduction

Composite materials have been subject of permanent interest of various specialists during the last decades. Firstly, military applications in the aircraft industry triggered off the commercial use of composites after the Second World War. The innovations in the composite area have allowed significant weight reduction in structural design. Composites offer many advantages when compared to metallic alloys, especially where high strength and stiffness to weight ratio is concerned. Additionally, they provide excellent fatigue properties and corrosion resistance in applications \cite{1}. With all these advantages, composite structures have gained widespread use in the aerospace industry during the last decades \cite{2–6}.

In the fifties, an important goal of aircraft materials development was to improve the crack growth properties of structural materials \cite{7}. Competing materials like advanced aluminium alloys and fibre reinforced composites have potential to increase the cost effectiveness of the structure. These materials still have their advantages and disadvantages, like the poor fatigue strength of the aluminium alloys and the poor impact and residual strength properties of carbon fibre reinforced composites. At the end of the seventies, the idea of using the two materials to form a hybrid composite structural material to overcome most of the disadvantages of both materials was born \cite{8}. At the Delft University of Technology, it was found that the fatigue crack growth rates in adhesive bonded sheet materials can be reduced, if they are built up by laminating and adhesively bonding thin sheets of the material, instead of using on one thick monolithic sheet \cite{7}. The advantage becomes highly evident if cracks start in one of the sheets of the laminate only, the adhesive layers behaving as crack dividers. Under these circumstances, the sheets that are still uncracked reduce the crack growth rate in the cracked sheet. The reduction in the crack growth rates persists until a crack is initiated in the neighbouring sheet also. Based upon all the research, initial Fibre Metal Laminates material, ARALL (Aramid Fibre Reinforced Aluminium Laminate) was introduced at 1978 in the Faculty of Aerospace Engineering at the Delft University of Technology (DUT) \cite{3}. ARALL consists of alternating thin aluminium alloy layers (0.2 ± 0.4 mm) and uniaxial or biaxial aramid fibre prepreg, as shown in Fig. 1 \cite{8}.
Fibre metal laminates (FMLs) are hybrid composite structures based on thin sheets of metal alloys and plies of fibre reinforced polymeric materials [6]. The fibre/metal composite technology combines the advantages of metallic materials and fibre reinforced matrix systems. Metals are for instance isotropic, have a high bearing strength and impact resistance and are easy to repair, while full composites have excellent fatigue characteristics and high strength and stiffness. The fatigue and corrosion characteristics of metals and the low bearing strength, impact resistance and reparability of composites can be overcome by the combination [5,9].

These material systems are created by bonding composite laminate plies to metal plies [8]. The concept usually applied to aluminium with aramid and glass fibres, but also can be applied to other constituents [10]. Fig. 2 gives a classification of FML based on metal plies. The most commercially available FMLs are ARALL1, based on aramid fibres and GLARE1 based on high strength glass fibres [8]. These two grades of FMLs are going to be explained in detail Chapter 3.

1.1. Historical development of fibre metal laminates

During the last three decades, there has been a search for lightweight materials that can replace the traditional aluminium alloys in aerospace structures [11]. For an optimal structural design, a
new material is needed which combines high strength, low density and high elasticity modulus with improved toughness, corrosion resistance and fatigue properties. Fibre reinforced composites materials almost cover all these demands, except for fracture toughness.

In 1978, researches were carried out to increase the fatigue performance of aluminium alloys at the National Aerospace Laboratory and at the Delft University of Technology in Netherland. An improvement of the fatigue behaviour in laminate sheet materials was obtained by introducing a high strength aramid fibre into the adhesive layers. As a result of all these studies, they introduced ARALL, first fibre metal laminate at the Faculty of Aerospace Engineering at the Delft University of Technology in Netherland [3]. In 1984, two international patents were accepted and a pilot production of four different types of standardized ARALL was started by the Alcoa Company after sufficient confidence in this material had been gained [7]. The trades ARALL 1 and ARALL 2 were standardized. Arall 1 is a variant with aluminium 7075 layers and Arall 2 uses aluminium 2024 layers and it was in the as-cured condition [1].

Later, a much stiffer ARALL which consists carbon fibres instead of aramid fibres, the CARALL Laminates, had been investigated in DUT [12]. Recent research has shown that CARALL laminates also have fibre failure occurred during flight-simulation fatigue tests at elevated stress levels, which resulted in poor fatigue performance. The limited failure strain of the carbon fibres (0.5–2.0%) was thought to be a disadvantage. Thus, it is sensitive to notch behaviour comparing to monolithic aluminium alloy. Due to the problem of galvanic corrosion between the carbon fibres and the aluminium sheet in moisture environment, more research has to be done.

In 1990, another attempt to improve ARALL laminates, adopting high strength glass fibre instead of aramid fibres, called GLARE (Glass reinforced, or ARALL with glass fibres) was developed successfully [7]. Glass reinforced aluminium (GLARE) is the successor of Aramid aluminium laminate (ARALL) [12]. A partnership between AKZO and ALCOA started to operate in 1991 to produce and commercialize GLARE [1].

Finally, a new concept for fibre metal laminates (ARALL & GLARE), the Spliced Laminates, is launched by the Structural Laminate Company (SLC) in 1992. Spliced laminates are defined as FML in which the aluminium layers are interrupted such that the dimensions of the spliced sheets depend on the autoclave dimensions only [7].

1.2. Advantages and disadvantages of fibre metal laminates

Fibre metal laminates take advantages of metal and fibre-reinforced composites, providing superior mechanical properties to the conventional lamina consisting only of fibre-reinforced lamina or monolithic aluminium alloys [9]. Table 1 summarizes all the advantages of fibre metal laminates depending on previous studies.

The major disadvantage associated with epoxy based fibre metal laminates is the long processing cycle to cure the polymer matrix in the composite plies [6]. This problem increases the cycle time of whole production and decreases productivity. This increases labour costs and overall cost of FMLs.

1.3. Production of FMLs

To produce FMLs, as for polymeric composite materials, the most common process involves autoclave processing. The overall generic scenario for production of FMLs involves about five major activities.

1. Preparation of tools and materials. During this step, the aluminium layer surfaces are pre-treated by chromic acid or phosphoric acid, in order to improve the adhesive bonding between metallic layer and fibre reinforced laminate (metallic surface treatment is explained in detail in Chapter 2).
2. Material deposition, including cutting, lay-up and debunking.
3. Cure preparation, including the tool cleaning and the part transferring in some cases, and the vacuum bag preparation in all cases.
4. Cure, including the flow-consolidation process, the chemical curing reactions, as well as the bond between fibre/metal layers.
5. Post stretching, after the hot-curing (200 °C) cycle in the autoclave, the fibre metal laminates carry a residual stress system over the thickness of the material with a small tensile stress in the aluminium sheets and compression in the fibres, this situation adversely effects fatigue resistance of FMLs. Post stretching operation after curing cycle can reverses the residual stress system and solves this problem.
6. Inspection, usually by ultrasound, X-ray, visual techniques and mechanical tests [17]. Mechanical tests of FMLs are explained widely in Chapter 4.

1.4. Applications

Due to their advantages aforementioned above, FMLs are finding great use in most commonly in aerospace applications. A number of companies have interest in substitute the traditional aluminium components by FML composites [5]. Both ARALL and GLARE laminates are now being used as structural materials in aircrafts. Fibre Metal Laminates have been successfully introduced into the Airbus A380 [4]. The Fig. 3 shows FML composite applications in the Airbus A380 airplane [1,18]. ARALL has been developed for the lower wing skin panels of the former Fokker 27 aircraft and the cargo door of the Boeing C-17 [8,10]. ARALL 3 material is currently in production and flight test on the C-17 cargo doors and GLARE is selected for the Boeing 777 impact resistant bulk cargo floor.

2. Adhesive bonding

Adhesive bonding process has been used in the manufacture of aircraft structures and components for 30–40 years [19]. Bonding techniques are used in an ever-growing number of applications: electronics (multilayer boards, bounded components), aerospace and aeronautical industries (F-18 bonded wings), automotive industries and many more organizations. Bonding structural components with adhesives offers many advantages over conventional mechanical fasteners: lower structural weight, lower fabrication cost, and improved damage tolerance [20]. Light weight sandwich construction and structural bonded joints form a major proportion of modern aircraft [21]. Modern metallic bonded structures using longitudinal lap joints in commercial aircrafts were introduced with the advent of the Airbus A300 [19]. As stated in Ref. [19], this technique is currently migrating from secondary to primary structural applications as one of the most interesting ways to fasten structural parts with a high level of confidence. For example, structural adhesive bonding is mainly used for attaching stringers and/ or tear straps to the fuselage and wing skins, to stiffen the structures against buckling. It is also applied to skin-to-core bonding in metallic honeycomb structures, such as elevators, ailerons, spoilers, and so on [22]. Bonded structures have been shown to be far more fatigue resistant than equivalent mechanically fastened structures and when designed correctly, can sustain higher load levels than equivalent mechanically fastened joints [21].
Advantages of fibre metal laminates.

| Material behaviour | 1. High fatigue resistance: It is achieved by the intact bridging fibres in the wake of the crack, which restrain crack opening. FMLs have excellent fatigue characteristics [5,13]. |
|--------------------| 2. High strength: As mentioned before, FMLs are hybrid structures based on thin sheets of metal alloy and plies of fibre-reinforced polymeric materials. Combination of metal alloys which have high bearing strength and fibre reinforced composites which have high strength and stiffness. FMLs are structural materials with high strength [4,5]. |
|--------------------| 3. High fracture toughness: Depending on the studies, FMLs have better fracture toughness than their constituent alloys. Based on this behaviour and accounting for the lower fatigue crack growth rates presented by these materials, they can be a very attractive option for a wide set of structural applications [14]. |
|--------------------| 4. High impact resistance: Unlike composites, the damage tolerance behaviour of FML is comparable to conventional aluminium alloys. The same types of damage and plastic deformation are observed, only at higher impact energy levels. Impact deformation is actually a significant advantage of FML, especially when compared to composites, because this visible damage significantly increases inspect ability and detect ability. Therefore, the use of FML allows for repair criteria and techniques [8,15]. |
|--------------------| 5. High energy absorbing capacity: Based upon researches, FMLs are capable of absorbing significant energy through localized fibre fracture and shear failure in the metal plies [6,16]. |

Physical properties

| Durability | 1. Excellent moisture resistance: The moisture absorption in FML composites is slower when compared with polymer composites, even under the relatively harsh conditions, due to the barrier of the aluminium outer layers [1]. Additionally prepreg layers are able to act as moisture barriers between the various aluminium layers inside of the FMLs [13]. |
|------------| 2. Excellent corrosion resistance: As mentioned above excellent moisture resistance of FMLs and high corrosion resistance of polymer based fibre laminates ensures FMLs excellent corrosion resistance [7,8,10,13]. |
|------------| 3. Lower material degradation: FMLs have excellent moisture and corrosion resistance, FMLs degradation as result of environmental aspects is significant lower as compared to either metallic structures, or composite structures [5]. |

Safety

| Safety | 1. Fire resistance: The high melting point of the fibres in FML (for instance, glass fibres in GLARE laminates can withstand 1100 °C) prevents penetration of the fire to the inner layers. Hence, the fire resistance of FMLs are much better than monolithic aluminum alloys depending on their fibre melting point. FMLs are being used as fuselage materials in aircrafts. With their good fire resistance, FMLs ensures enough time to passengers for evacuating the aircraft safely [8,17]. |
|---------| 2. Owing to fatigue insensitivity of FMLs, less repair and longer maintenance periods are sufficient for FMLs. These advantages reduce maintenance costs of FMLs [7]. |

Cost saving

| Cost saving | 1. FML offer substantial weight savings relative to current metallic structures. Further, the number of parts required to build a component may be dramatically less than the number of parts needed to construct the same component of metal alloy. This can lead to labour savings. Sometimes offsetting the higher price of the present materials |
|-------------| 2. Owing to fatigue insensitivity of FMLs, less repair and longer maintenance periods are sufficient for FMLs. These advantages reduce maintenance costs of FMLs [7]. |

As reported in Ref. [19], early experiences in bonding techniques demonstrated that surface treatment prior to bonding is the single most critical step which can not be disregarded, even for tertiary-loaded structures, since it is essential to achieve long-term service capability [21,23]. A particular surface treatment tends to modify the substrate surface by delivering the following features: free from contamination; wettable with either primer or adhesive; highly roughened; and mechanically and hydrolytically stable [23]. Surface treatment technologies need to be explained from the viewpoint of adhesively bonded fibre-metal laminate research.

3. Surface treatments for adhesive bonding

As shown in Table 2, all the treatments for modification of metal surfaces can be grouped as:

1. Mechanical.
2. Chemical.
3. Electrochemical.
5. Dry surface treatments.

Solvent degreasing is important, because it removes contaminant materials which inhibit the formation of the chemical bonds. However, solvent degreasing, while providing a clean surface, does not promote the formation of acceptable surface conditions for longer term bond durability [21]. The degreasing stage usually makes use of chlorinated solvents such as trichloroethylene, 1,1,1-trichloroethane, perchloroethylene, or dichloromethane, or alternatively, non-chlorinated solvents including methyl ethyl ketone, methanol, isobutanol, toluene or acetone [24]. All aluminium alloy sheets were initially degreased prior to further surface...
pre-treatment steps. The first step in the fabrication of baseline test specimens was methyl ethyl ketone (MEK)-wiping of aluminium substrates with lint-free tissues to degrease the surface [25]. Each surface treatment technologies which have been used to modify metal surfaces will be explained in detail in subtitles of Section 3.

3.1. Mechanical treatment

As a preliminary preparation step in the multi-stage schedules, mechanical abrasion has been used to produce a macro-roughened surface, different roughness levels of the surface textures and to remove an undesirable oxide layer, respectively [19]. This method typically involves abrasive scrubbing of the substrate surface with sand paper. This mechanical treatment would introduce physico-chemical changes which yield a wettable surface and modify the surface topography, i.e., a macro-roughened surface [27].

Mechanical treatments include abrasion methods usually combined with degreasing. Pretreatment by blasting using alumina or silica grit or glass beads change the topography and chemical state of the aluminium adherend by the introduction of a “peak-and-valley” type morphology [24]. In general terms, degreasing is the minimum pretreatment that is usually carried out prior to bonding. Grit-blasting or other mechanical abrasion methods are recognized as providing a useful increase in initial adhesion levels [24]. Several researches have highlighted different aspects of grit blasting or other mechanical abrasion methods for aluminum alloys. Grit-blasting, which uses alumina grit with clean, dry, propellant air, is employed as a logical surface activation step prior to modify the metallic surface for satisfactory bonding results [26–29].

3.2. Chemical treatment

The most commonly applied chemical treatments are based on a chromic–sulphuric acid etch [23,37]. This treatment consists of immersion of the substrate in a solution of sulphuric acid and potassium dichromate. Typically, chemical treatment, i.e., acid-etching, is an intermediate production step between degreasing, alkaline cleaning, and electrochemical treatment [19]. Three classical acid-etching solutions were introduced to modify the metallic surfaces: chromic–sulphuric acid (CAE) [38], Forest Product Laboratory (FPL) [25], and sulfo-ferric acid (P2) etches. The most effective etches incorporate mixed chromic and hydrofluoric acids. However, non-chromated acid etchants have been demonstrated to provide good adhesion results [23,39]. The surfaces treated with acid-etch were consistently reported to be out-performed by anodized surfaces so that the inconsistent results made them unsuitable for stand-alone treatment in primary bonded structures [23]. Chemical acid etches are given in Table 3 with concentration of compounds, used temperature and immersion time.

3.3. Electrochemical treatment

Good adhesion between the metal and the adhesive could be obtained when the aluminum surfaces were degreased in alkaline solutions or organic solvents and subsequently etched in aqueous chromic–sulphuric acid solutions. However, this surface pre-treatment was found to be insufficient in certain non-bonded areas where corrosion occurred. The corrosion susceptibility was reduced if the aluminium surface, after chromic–sulphuric acid etching, was anodized before bonding [34]. In order to obtain optimum durability of adhesive bonded aluminium joints, anodizing processes are extensively used in the aerospace industry. Anodizing produces a thin oxide film, again with a high degree of micro-roughness and an oxide form which is highly resistant to hydration [21]. Anodic oxidation in solutions of chromic acid anodizing (CAA) or phosphoric acid anodizing (PAA) is the preferred stabilizing treatment for the structural adhesive bonding of high-strength aluminium alloys in critical applications such as aircraft components [35]. Chromic acid anodizing (CAA) was found to give a relatively thin and ductile oxide layer and was established as an effective pretreatment for adhesive bonding with good durability properties in service. The European aviation industry is still using this method [36]. However, as a result of delamination in the boundary zone and corrosion after only a few years of operation, an improvement of the usual FPL process was established. Boeing developed the phosphoric acid anodizing (PAA), which led to a clearly better joint durability [23,34].

As stated in Ref. [24], in almost all studies, however, the DC electrochemical pretreatments give the best levels of initial adhesion and durability [23,36,40,41]. The three most widely used

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**Table 2**

All treatments for modification of metal surfaces.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Nature of treatments</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grit-blasting</td>
<td>Mechanical</td>
<td>[26–29]</td>
</tr>
<tr>
<td>Chromic–sulphuric acid (CAE)</td>
<td>Acid etching</td>
<td>[30,33]</td>
</tr>
<tr>
<td>Sulfo-ferric acid (P2)</td>
<td>Acid etching</td>
<td>[31]</td>
</tr>
<tr>
<td>Forest Product Laboratory (FPL)</td>
<td>Acid etching</td>
<td>[32]</td>
</tr>
<tr>
<td>Alkaline</td>
<td>Etching</td>
<td>[25,30]</td>
</tr>
<tr>
<td>Chromic acid anodizing (CAA)</td>
<td>DC-anodizing</td>
<td>[46]</td>
</tr>
<tr>
<td>Phosphoric acid anodizing (PAA)</td>
<td>DC-anodizing</td>
<td>[23,34,36]</td>
</tr>
<tr>
<td>Sulphuric acid anodizing (SAA)</td>
<td>DC-anodizing</td>
<td>[36,45]</td>
</tr>
<tr>
<td>Boric-sulphuric acid anodizing (BSAA)</td>
<td>DC-anodizing</td>
<td>[24]</td>
</tr>
<tr>
<td>Sulphuric acid anodizing (AC-SAA)</td>
<td>AC-anodizing</td>
<td>[36]</td>
</tr>
<tr>
<td>Silane</td>
<td>Coupling/oxidation</td>
<td>[28,47,49–52]</td>
</tr>
<tr>
<td>Sol–gel</td>
<td>Coupling/oxidation</td>
<td>[53–57]</td>
</tr>
<tr>
<td>Excimer laser texturing</td>
<td>Mechanical</td>
<td>[54,58–62]</td>
</tr>
<tr>
<td>Plasma sprayed coating</td>
<td>Ablation/oxidation</td>
<td>[35,63–67,69]</td>
</tr>
<tr>
<td>Ion beam enhanced deposition (IBED)</td>
<td>Ablation/oxidation</td>
<td>[62,68]</td>
</tr>
</tbody>
</table>

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**Table 3**

Chemical acid etches and their application process.

<table>
<thead>
<tr>
<th>Acid-etch type</th>
<th>Application process</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAE</td>
<td>Immersion in a water solution with 330 ml/l chromic–sulfuric acid (97% v/v) and 50 g/l potassium dichromate, at 60 °C for 15 min, and rinsed in tap water</td>
<td>[30]</td>
</tr>
<tr>
<td></td>
<td>Immersion in a water solution with 185 ml/l chromic–sulfuric acid (97% v/v) and 127 g/l ferric sulphate, at 65 °C for 8 min, and rinsed in tap water (percentages by weight: 48% H,O, 37% HSO₄ and 15% FeSO₄)</td>
<td>[30]</td>
</tr>
<tr>
<td></td>
<td>Immersion at 15 min in a 65 °C, followed by tap and de-ionised water rinsing</td>
<td>[33]</td>
</tr>
<tr>
<td>P2</td>
<td>Involves treatment of the adherend surface with an aqueous acidic solution containing Fe(III), (1) immersing the adherend in the P2 solution at 65 °C for 8 min, (2) rinsing the specimen in DI water for 2–3 min, and (3) drying the aluminium bars in an oven at 60 °C for 30 min. The P2 solution was prepared by dissolving 122.5 g Fe₂(SO₄)₄·12H₂O and 0.185 l of concentrated sulphuric acid in enough water to make a liter of solution</td>
<td>[31]</td>
</tr>
<tr>
<td>FPL</td>
<td>Treat with optimized FPL for 30 min at 62 ± 2 °C. After treatment in the acid, the aluminium was washed for 20 min in cold running tap water and finally dried in an oven at 40 °C for 30 min</td>
<td>[32]</td>
</tr>
<tr>
<td>Alkaline etch</td>
<td>Immersion in 100 g/l NaOH solution, at 60 °C for 1 min, and rinsed in tap water</td>
<td>[30]</td>
</tr>
<tr>
<td></td>
<td>Immersion in 310 wt. NaOH solution for 2 min at 60 °C</td>
<td>[25]</td>
</tr>
</tbody>
</table>
electrochemical processes used in prebond applications are phosphoric acid anodizing (PAA), chromic acid anodizing (CAA) and sulphuric acid anodizing (SAA). Other electrolytes have been studied but to a much lesser extent. CAA and PAA are both extensively used in aerospace applications [42,43]. All DC anodizing procedures are complex multi-stage operations incorporating degreasing, desmutting and oxidizing stages [34]. The boric–sulphuric acid anodizing (BSAA) process has advantages associated with both the CAA and PAA. A BSAA process has been patented by Boeing as a direct replacement to CAA to meet environmental regulations [44]. AC anodizing is a highly feasible, robust, and environmentally friendly process, which is free from the hexavalent chromium found in the conventional CAA. A distinct difference from DC anodizing is hydrogen gas generation on the treated surface during the hot AC anodizing process [19]. Electrochemical treatments which are used for improving the metallic surfaces as an adhesive layer are shown in Table 4.

### 3.4. Coupling agent treatment

There is an ongoing need to develop environmentally friendly coupling agent techniques, i.e., silane or sol–gel, which can be used with the current generation of materials, i.e., primer and film adhesive [19]. Silane based products are becoming an interesting material for pre-treatment deposition, because, for the environmental compatibility, they can be used as substitutes of traditional pre-treatments like chromates [47]. Silane coatings are environmentally sound, multi-metal surface pre-treatments, considered for use on various metals such as aluminium and its alloys, copper, iron and steel, zinc and magnesium containing alloys [48]. It is sufficient to mention that a large number of studies have demonstrated the usefulness of silanes such as γ-glycidoxypropyltrimethoxysilane when used as a primer to improve the durability of structural aluminium bonds. This has been attributed to the formation of stable, covalent bonds between the metal(oxide) and the silane and the possibility for interphase formation giving a region of intermediate modulus between the metal and polymer which facilitates stress transfer [49,50]. Bis-1,2-(triethoxysilyl)ethane (BTSE) has received much attention as it is, after hydrolysis, highly reactive towards (covalent) metal/film bonding and cross-link formation for the creation of barrier properties [52]. Fedel et al. [47] examined the effect of water-based silane pre-treatments on galvanized steel. Three different silanes were used for the pre-treatment deposition (glycidoxypropyltrimethoxysilane, tetraethoxysilane and methyltriethoxysilane). The electrochemical tests showed that the silane layer acts not only as a coupling agent between the inorganic substrate and the organic coating, but it also ensures a good barrier effect against water and oxygen. Rider and Arnott [28] described that the silane layer promotes the hydrolytic stability of the adhesively bonded joint, leading to increased durability in wedge tests.

Sol–gels are organic–inorganic polymers formed by hydrolysis/condensation reactions of alkoxide precursors, primarily silanes, which have found applications as electronic, optical and protective coatings. These coatings possess important characteristics such as chemical stability, physical strength and scratch resistance. The sol–gel process can be used to form nanostructured inorganic films (typically 200 nm to 10 μm in overall thickness) that are more resistant than metals to oxidation, corrosion, erosion and wear while also possessing good thermal and electrical properties [53]. As noted in Ref. [19], sol–gel which involves the growth of metal–oxo polymers through both hydrolysis and a condensation reaction to form inorganic polymer networks in thicknesses ranging from 50 to 200 nm [54,55]. The Boegel EPII sol–gel agent consists of a dilute aqueous epoxy-silane and zirconium alkoxide. This mixture provides a thin inorganic zirconium oxide film incorporated with the epoxy-silane that is applied to the metallic surface [55,56]. In this process, zirconium reacts with the metallic surface to produce a covalent chemical bond, while the epoxy-silane offers a reactive organic group for bonding with the adhesive [55,57].

### 3.5. Dry surface treatments

Several dry treatments for aluminium alloy surfaces have been developed to replace chemical wet treatment process: excimer laser texturing [54,58–62], plasma-sprayed coating [35,63–67], and ion beam enhanced deposition (IBED) [62,68].

As reported in Ref. [19], laser texturing was utilized to modify an aluminium substrate’s morphology and micro-structure, resulting in an increased bond strength and durability [58,59,62]. IBED is a process that cleans and modifies the surface by sputtering with high energy argon ions under vacuum. This process requires a surface activation step, particularly grit-blasting, prior to IBED. Good initial bond strengths were obtained and the improvements in wedge durability compared with PAA were found [62]. In the aeronautic industry, a complex and critical process is used in order to enhance both wettability and adhesive properties of aluminium alloy surfaces.

Cold plasma treatment represents an alternative to conventional processes in terms of environmental impact. Plasma is an ionized gas containing both charged and neutral particles, such as electrons, ions, atoms, molecules and radicals. There are two kinds of plasma: cold and hot. The working pressure of a cold plasma is generally lower than atmospheric pressure which allows the production of chemical reactive species at low temperatures (<773 K). Since hot plasma pressure is higher than atmospheric, the temperature is about 10^4–10^5 K [35]. Cold plasma treatment represents an efficient, clean and economic alternative to activate surface treatments [67]. Plasma spray coatings were also used as pretreatments prior to adhesive bonding. Davis et al. [63] reported that a 60Al–Si/40 polyester (by wt.) plasma spray coating could be engineered for specific applications and was better suited for the adhesive bonding process of aluminium substrates, by yielding a performance equivalent to that of the PAA treatment with some epoxy adhesives in the wedge test. De Iorio et al. [69] examined cold plasma treatments to modify the surface properties of polymeric materials (polystyrene–polyamide, polycarbonate–ABS) and A1 6061 alloy, with the aim of increasing the surface adhesion in structural joints.

### 4. Mechanical bonding

As reported at Ref.[73], the increasing requirements for weight reduction demand more and more use of composite materials in

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**Table 4**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Electrolyte (wt.%</th>
<th>Voltage (V)</th>
<th>Time (min)</th>
<th>Temperature (°C)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAA</td>
<td>(H₂PO₄)</td>
<td>10 (DC)</td>
<td>20</td>
<td>25</td>
<td>[36]</td>
</tr>
<tr>
<td>SAA</td>
<td>(H₂SO₄)</td>
<td>1.5 (DC)</td>
<td>20</td>
<td></td>
<td>[36]</td>
</tr>
<tr>
<td>BSAA</td>
<td>5.0–10.0 H₂BO₃/30.0–50.0 H₂SO₄</td>
<td>15 ± 1 (DC)</td>
<td>18–22</td>
<td>26.7 ± 2.2</td>
<td>[24]</td>
</tr>
<tr>
<td>SAA</td>
<td>(current density A/dm²)</td>
<td>15 (DC)</td>
<td>22</td>
<td>15</td>
<td>[45]</td>
</tr>
<tr>
<td>CAA</td>
<td>2.5–3.0 CrO₃</td>
<td>40.0 ± 1.0</td>
<td>35–40.0 ± 2.0</td>
<td>45</td>
<td>[46]</td>
</tr>
<tr>
<td>PAA-AC</td>
<td>(H₂PO₄)</td>
<td>4 (AC)</td>
<td>30</td>
<td>50</td>
<td>[36]</td>
</tr>
<tr>
<td>SAA-AC</td>
<td>(H₂SO₄)</td>
<td>10 (AC)</td>
<td>12</td>
<td>80</td>
<td>[36]</td>
</tr>
</tbody>
</table>

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*Note: AC anodizing replaces conventional CAA. A distinct difference from DC anodizing is hydrogen gas generation on the treated surface during the hot AC anodizing process [19]. Electrochemical treatments which are used for improving the metallic surfaces as an adhesive layer are shown in Table 4.*
aerospace applications [70]. There has been a progressive increase in the number of metal parts and structures replaced by composite materials, not only in military, but also in civil aircraft design. For instance, composite materials comprise 22% of the total weight of the Airbus A380 [71]. The centre wing box, the tail cone, the pressure bulkheads and the vertical and horizontal tails are only some of numerous parts of this modern aircraft [72] being made of composite materials. Structural coupling leads to an increase in structural complexity and to additional local stress factors, but also to a considerable reduction in global optimizing possibilities, which, in turn, decreases the lightweight potential of composite design. Thus, the development of advanced joining technologies designed to minimize the weight penalties produced by structural coupling gains a new meaning in the present situation. This is especially true for concentrated load transmissions, as it is the case for mechanically fastened joints [73]. Mechanical fastening is still one of the main methods currently used for joining composite components [70], with the advantage of no special surface preparations, easy disassembly and inspection.

Hybrid bolted bonded (HBB) joining technology in lap joints combines both classical techniques, i.e. bolting and bonding. The advantages of HBB joints, compared to bolted joints, could be summarized in two main points: (i) continuous instead of discrete load transfer distribution along the overlap and (ii) decrease of load transferred by fasteners. Furthermore, in terms of security, the existence of fasteners in HBB joints could ensure the functioning of the structure, even if the adhesive layer failure occurs. In manufacturing industries in which numerous bolted and riveted joints are used, the use of HBB technology could be considered as a potential solution, in order to reduce the mass as well as the manufacturing cost [74].

As stated at Ref. [73], the mechanical behaviour of composite bolted joints has been extensively studied in the past by means of experimental, analytical and numerical approaches [75–81], mainly focusing on the determination of the load capability, the load and stress distributions and failure criteria of single- and multi-row bolted joints under the influence of varying laminate configurations and joint geometries. One of the most effective ways to improve the load capacity of composite bolted joints entails the local reinforcement of the composite laminate with high-strength metal layers [82–84], thus clearly improving its bearing and shear capabilities. The special feature of this reinforcement technique consists of only embedding the metal layers into the bolted joining area locally, which is accomplished either by ply-addition (metallic layers are inserted between the composite plies [82]) or ply-substitution techniques (composite plies are replaced by metallic layers [84]). Hence, the total load capability of this reinforcement approach depends not only directly on the load capability of the bolted joint, but also on the strength of the transition zone between the pure fibre composite material and the hybridized laminate region.

5. Fibre metal laminates

5.1. Arall

The idea of putting fibre reinforcement in the adhesive bond lines between aluminium alloys has been researched at many laboratories over the past three decades. These researches made it possible to develop first fibre metal laminates. Finally in 1978, ARALL has been developed at the Faculty of Aerospace Engineering at the Delft University of Technology in Netherland. In 1982 the first commercial product under the trade name ARALL was launched by ALCOA.

ARALL laminates are made of high strength aramid fibres embedded in a structural epoxy adhesive sandwiched between multiple layers of thin aluminium alloy sheets. A schematic presentation of ARALL is shown in Fig. 1. Combination of high strength metals (aluminium layers) and strong fibres (aramid) generates a new composite material with a unique set of properties. ARALL laminates offer many advantages such as high strength and excellent fatigue properties. Moreover, they retain the advantages of aluminium alloys, namely lower cost, easy machining, forming, and mechanical fastening abilities, as well as substantial ductility [1,3,85,86].

In the ARALL concept, unidirectional fibre prepregs are used. This concept is very tolerant of material inconsistencies. The fibre orientation is chosen into the direction of the main load. The laminates are designed such that the fibres do not fail, when fatigue cracks develop. That means they remain intact behind the tip of the propagating crack in the metallic layers. They hinder the opening of the crack, and consequently, the crack tip stress intensity in the aluminium sheet is reduced. Fig. 4 shows the crack bridging mechanism of the ARALL laminates.

The fibres are insensitive to the fatigue loading, which key benefit of this material regarding crack propagation. The prepreg transfers loads over the crack, decreasing the stress intensity at the crack tip and reducing the crack growth rate. As a result of crack bridging mechanism, the crack growth life of FMLs is significantly extended compared to monolithic aluminium. Crack bridging is related to the crack opening, the loads are initially mainly transferred through the aluminium sheets until a certain crack opening is reached [7,12,87,88]. This behaviour can lead to improvement in the crack growth rates by a factor of a hundred and even more, as compared to monolithic aluminium alloy sheet. This improvement also allows for weight savings up to 30% in fatigue-critical aircraft components. Comparison of ARALL laminates on a structural level with other aircraft materials show that, ARALL laminates are very attractive materials, especially for fatigue dominated structural parts, such as the lower wing skin and the
pressed fuselage cabin of an aircraft. In this way a new hybrid material ARALL has been obtained. In 1984 two international patents were accepted and a pilot production of four different types of standardized ARALL was started by the Alcoa Company after sufficient confidence in this material had been gained [7]. Commercialized ARALL laminates are given in Table 5 [89].

All four standard ARALL products employ a thermoset adhesive system impregnated with unidirectional aramid fibres in a fibre to resin weight ratio of 50:50. The fibres are oriented parallel to the aluminium sheet rolling direction. ARALL laminates are produced under very rigid quality control standards. The aluminium sheets are anodized and primed according to existing aerospace industry specifications. Both chromic acid anodizing and phosphoric acid anodizing treatments are used. The outer aluminium surfaces can be left bare for later processing after an ARALL part has been formed. Table 6 summarizes production parameters of ARALL laminates.

ARALL panels are laid up and cured under the appropriate times and temperatures either in mechanical press or an autoclave. After curing, the aluminium layers are in a slight tensile residual stress state and the prepreg layers in a compensating compressive residual stress state. The ARALL 1 and 3 laminates are given a postcure regime. Table 6 summarizes production parameters of ARALL laminates.

As mentioned before; ARALL has been developed for the lower wing skin panels of the former Fokker 27 aircraft and the cargo door of the Boeing C-17. Later with new developments, ARALL has been used in wide range of fields and applications. They were used in fuselage and wing structures in aerospace applications and used as a ballistic material in military applications. However, they are mostly used as a structural material in cargo doors of aircrafts [8,10,90].

5.2. Glare

GLARE laminates belong to fibre metal laminates family, they consist of alternating layers of unidirectional glass fibre reinforced prepgregs and high strength aluminium alloy sheets. At first, they were developed for aeronautical applications as an improvement of ARALL with advanced glass fibre and introduced at the Technical University of Delft in Netherlands in 1990. Later, a partnership between AKZO and ALCOA started to operate in 1991 to produce and commercialize GLARE [1,7,91,92]. Fig. 5 schematically illustrates a cross-ply GLARE laminate.

The biggest differentiation of GLARE compared to ARALL is that GLARE consists of glass fibres instead of aramid fibres. This diversity gives superior properties to GLARE laminates. Table 7 highlights the advantages and disadvantages of various fibres for FMLs.

The specific stiffness and strength in the fibre direction of GLARE are enhanced over the high strength aluminium alloy used for the metal layers, which significantly contributes to weight savings in the designs of tension-dominated structural components. Aforementioned fibre bridging mechanism impedes the growth and propagation of cracks in the aluminium-alloy layers under tensile fatigue loading conditions [91]. GLARE has a better adhesion between the glass fibres compared to ARALL. Moreover, glass fibres are much more resistant to compression loading. As a consequence, fibre failure in the glass fibres has rarely been observed during in fatigue load. Other advantages of GLARE over ARALL are its higher tensile and compressive strength, better impact behaviour and better residual strength. Better adhesion between glass fibre and resin makes GLARE laminates with fibres built up in two directions is possible. This being is much more suitable for some constructions where biaxial stresses occur. These properties seem to make GLARE has a wider range of potential application [7].

Nowadays, GLARE materials are commercialized in six different standard grades (Table 8). They are all based on unidirectional glass fibres embedded with epoxy adhesive resulting in prepregs with a nominal fibre volume fraction of 60%. During fabrication of composites the prepregs are laid-up in different fibre orientations between aluminium alloy sheets, resulting in different standard GLARE grades. For the GLARE 1, GLARE 2, GLARE 4 and GLARE 5 the composite laminate, i.e. the fibre/resin layer, are stacked symmetrically. In the case of GLARE 3 composite, the composite laminate have a cross-ply fibre layer stacked to the nearest outer aluminium layer of the laminate, in relation to the rolling direction of the aluminium. For the GLARE 6 composite, the composite layers are stacked at +45° and −45°. Table 8 shows these grades, including the most important material advantages [1]. GLARE is produced with a standard bonding technology. After the hot-curing (120 °C) cycle in the autoclave, the fibre-metal laminates carry a residual stress system over the thickness of the material, with a small tensile stress in the Al-sheets and compression in the fibres: this is not favourable for fatigue behaviour. A post-stretching operation after the curing cycle can reverses the residual stress system and solve the problem, thus a tension stress occurs in fibres and compression in the Al-sheets. But post-stretching causes extra production cost and it is practically impossible for wide panels [7]. Due to unique combination of properties, GLARE can be ap-

---

**Table 5**
Commercially available ARALL laminates [89].

<table>
<thead>
<tr>
<th>Metal type</th>
<th>Metal thickness (mm)</th>
<th>Fibre layer (mm)</th>
<th>Fibre direction (°)</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARALL 1</td>
<td>7075-T6</td>
<td>0.3</td>
<td>0.22</td>
<td>0/0</td>
</tr>
<tr>
<td>ARALL 2</td>
<td>2024-T3</td>
<td>0.3</td>
<td>0.22</td>
<td>0/0</td>
</tr>
<tr>
<td>ARALL 3</td>
<td>7475-T76</td>
<td>0.3</td>
<td>0.22</td>
<td>0/0</td>
</tr>
<tr>
<td>ARALL 4</td>
<td>2024-T8</td>
<td>0.3</td>
<td>0.22</td>
<td>0/0</td>
</tr>
</tbody>
</table>

**Table 6**
Production parameters of ARALL laminates [86].

<table>
<thead>
<tr>
<th>Metal type</th>
<th>Cure resin</th>
<th>Cure temp.</th>
<th>Stretching</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARALL 1</td>
<td>AF-163-2</td>
<td>120 °C</td>
<td>0.4% permanent stretch</td>
<td>Superior fatigue resistance</td>
</tr>
<tr>
<td>ARALL 2</td>
<td>AF-163-2</td>
<td>120 °C</td>
<td>With or without 0.4% stretch</td>
<td>Excellent fatigue resistance</td>
</tr>
<tr>
<td>ARALL 3</td>
<td>AF-163-2</td>
<td>120 °C</td>
<td>0.4% permanent stretch</td>
<td>Superior fatigue resistance</td>
</tr>
<tr>
<td>ARALL 4</td>
<td>AF-191</td>
<td>175 °C</td>
<td>With or without 0.4% stretch</td>
<td>Excellent fatigue resistance</td>
</tr>
</tbody>
</table>
plied to wide range of applications. Manufacturers are giving lots of attention on GLARE. However, it has been mostly used in aerospace applications so far. Recently, GLARE is used in the main fuselage skin and the leading edges of the horizontal and vertical tail planes of new, high capacity Airbus A380. The latter application is a consequence of the excellent impact resistance of the FML concept utilizing the high strength glass fibres with strain rate effect \[9,10,86,87]. With excellent impact characteristics, GLARE is being evaluated for use as cockpit crown, forward bulkheads, the leading edge and the flame-resistant capability of GLARE makes it suitable for flame sensitive areas such as; fire walls, cargo-liners, etc. in aerospace applications [7].

5.3. Carall

Fibre metal laminates consist of alternating layers of aluminium alloy and adhesive impregnated fibres pregregs. Their superior properties depend strongly on the type of reinforcing fibres used in pregregs. Each type has its advantages and limitations. As mentioned before ARALL laminates are based on aramid fibres. Aramid fibres provide good specific strength and modulus, high impact resistance and outstanding toughness to ARALL laminates. However, the poor compressive strength is a major limitation for these hybrid composites. In this point of view, CARALL laminates has developed as an improvement of ARALL laminates. They contain different amount of carbon/epoxy pregregs instead of aramid/epoxy pregregs [93–95]. A schematic illustration of CARALL laminates is shown in Fig. 6.

Compared with aramid/epoxy, carbon/epoxy composites possess higher specific modulus, but relatively low values of specific strength, strain to failure and impact resistance. In terms of fatigue, it was recognized that aramid fibre composites have better low cycle fatigue performance but worse high cycle fatigue performance.

<table>
<thead>
<tr>
<th>Table 7</th>
<th>Identified advantages and disadvantages of various fibres for FMLs [93].</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fibre</td>
<td>Advantage</td>
</tr>
<tr>
<td>Aramid</td>
<td>Outstanding toughness</td>
</tr>
<tr>
<td></td>
<td>Excellent fatigue resistance in both tensile</td>
</tr>
<tr>
<td></td>
<td>and flexural fatigue loading</td>
</tr>
<tr>
<td></td>
<td>High Young’s modulus</td>
</tr>
<tr>
<td>Glass</td>
<td>Low weight</td>
</tr>
<tr>
<td></td>
<td>High tensile strength</td>
</tr>
<tr>
<td></td>
<td>High failure strain</td>
</tr>
<tr>
<td></td>
<td>Do not absorb moisture</td>
</tr>
</tbody>
</table>

Table 8

<table>
<thead>
<tr>
<th>Table 8</th>
<th>Commercially available GLARE grades [1,89].</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade</td>
<td>Sub</td>
</tr>
<tr>
<td>GLARE 1</td>
<td>–</td>
</tr>
<tr>
<td>GLARE 2</td>
<td>GLARE 2A</td>
</tr>
<tr>
<td></td>
<td>GLARE 2B</td>
</tr>
<tr>
<td>GLARE 3</td>
<td>–</td>
</tr>
<tr>
<td>GLARE 4</td>
<td>GLARE 4A</td>
</tr>
<tr>
<td></td>
<td>GLARE 4B</td>
</tr>
<tr>
<td>GLARE 5</td>
<td>–</td>
</tr>
<tr>
<td>GLARE 6</td>
<td>GLARE 6A</td>
</tr>
<tr>
<td></td>
<td>GLARE 6B</td>
</tr>
</tbody>
</table>
than carbon fibre composites. Moreover, the high stiffness of carbon fibres allows for extremely efficient crack bridging and therefore very low crack growth rates [90,96]. CARALL is produced similar to ARALL and GLARE laminates. Before the curing process, aluminium surfaces are treated for an optimal adhesion between aluminium alloy and epoxy resin. Then, they are cured in hot press. The combination of high stiffness and strength with good impact properties gives CARALL laminates a great advantage for space applications. Other applications for this laminate are impact absorbers for helicopter struts and aircraft seats [96].

6. Test methods of fibre metal laminate composites

6.1. Bending tests

Mechanical properties of composite materials are governed by the adhesion between fibre and matrix. Beside this, same properties of FMLs are governed by the interface bond between composite ply and metal ply. Determination of this adhesion is not an easy task therefore various test methods have been proposed in the literature for this purpose: interlaminar shear and interfacial fracture tests. These methods give quality control information and are not suitable for design specifications.

Interlaminar shear tests have been used to determine the interlaminar shear strength (ILSS) of FMLs for a long time [97–105]. According to the literature survey, there are three kinds of test methods according to the interlaminar shear loading types: I. Compression loading [97], II. Three and five-point bending [98–101,103,105] and III. Short beam shear loading [102,104]. These tests will be explained individually.

Hinz et al. [97] investigated interlaminar shear properties of FMLs by means of a double-notch shear test (DNS) according to ASTM D3846 at room temperature. The interlaminar shear load between the notches was primarily applied by compression on both ends of the DNS specimen as illustrated schematically in Fig. 7. According to author’s advice; for controlled deflection, a linear guided sliding carriage should be used. In this work a step motor applied the compression load with a constant carriage speed 0.06 mm/min. It is reported that the load was measured using a load cell with 500 N load capacities and recorded by means of a Kyowa CDV-700A measuring amplifier. The compressive stress is calculated using the cross section of the specimen. To calculate the applied interlaminar shear stress the effective area of the shear plane was used.

The other test methods applied for ILSS investigation of FMLs are three and five-point bending tests (Fig. 8). Lawcock et al. determined the ILSS of FMLs by three and five-point bending tests with a span of 10 mm at a crosshead speed of 1.3 mm/min [99]. The authors calculated the ILSS by Eq. (1) for three-point bending and five-point bending:

$$\text{ILSS} = \frac{33P_c}{(64Wt)}$$ (1)

where “$P_c$” is the initial load for interlaminar failure and “$W$” and “$t$” are the width and thickness of the specimens, respectively.

Other work; Lawcock et al. calculated ILSS of FMLs from three-point and five-point bending tests as follows [101]:

- Three-point bending: $$\text{ILSS} = \frac{(3P_{\text{max}})}{4Wt}$$ (2)
- Five-point bending: $$\text{ILSS} = \frac{(33P_{\text{max}})}{(64Wt)}$$ (3)

where “$P_{\text{max}}$” is the failure load and “$W$” and “$t$” are the width and thickness of the specimens, respectively.

Reyes and Cantwell also reported their investigation about ILSS of FMLs by means of three-point bending test [103]. These tests were undertaken at crosshead displacement rates between 0.1 and 3 m/s and were stopped once a visible crack had propagated from one of the starter defects. In all these studies; the authors
were not mentioned about test standards. However; Khalili et al. [105] reported that three-point bending tests were carried out on Zwick 1484 by using specifications of ASTM D790 M-93.

The last test method for investigating ILSS of FMLs is short beam shear test. Park et al. performed ILSS tests to evaluate the extent of hygrothermal degradations as a function of water absorption and thermal cycles [102]. ILSS of FMLs was evaluated by the ASTM D2344 standard specimen through a short beam shear test. They reported that tests were carried out with a crosshead speed of 1.3 mm/min. Botelho et al. [104] also used the same test standard (ASTM D2344) for investigating the ILSS of FMLs. Authors reported that the tests were performed with Instron mechanical testing machine using a test speed of 1.3 mm/min.

The next test method group for investigating the interface bonding between composite and metal plies is as mentioned above the interfacial fracture tests. In these tests, the degree of adhesion between the composite and metal plies was investigated using the single cantilever beam (SCB) geometry [103,106,107]. This geometry yields mixed-mode I/II loading (tension/shear) conditions at the crack tip in the sample. It is reported in these papers that SCB specimens with dimensions of 20 mm x 200 mm were removed from the moulded plates. The SCB specimens were clamped in the test fixture shown in Fig. 9 and tested at crosshead displacement rate of 0.04 mm/min.

According to these studies the interfacial fracture energy was determined using an experimental compliance method where the interfacial fracture energy, “Cf,” is given by:

\[ G_c = \frac{3P^2k^2}{2B} \]

where “P” is the applied force, “B” the specimen width, “C” the specimen compliance and “a” the crack length. Also it is mentioned that the specimen compliance was determined as a function of crack length and a curve fit of the following form applied:

\[ C = C_0 + ka^3 \]

where “C0” and “k” are constants for a given specimen. Here, it is told that the parameter “k” was determined by measuring the gradient of the plot of the compliance “C” versus the cube of the crack length “a” whereas it was not necessary to determine the values of “C0”.

6.2. Fatigue tests

The fatigue properties of fibre metal laminates have been evaluated in numerous test programs. Generally fatigue tests were conducted according to the ASTM standards. The shape and dimensions of specimens for fatigue testing were based on ASTM D3479; the specimen length \( L = 200 \) mm, the gauge length \( LG = 100 \) mm, the specimen width \( W = 25 \) mm [9,91,108]. Beside this Reyes and Kanga were conducted ASTM E466 test standard for analyzing fatigue behaviour of FML [109]. Except these papers there are many studies that fatigue performance of FMLs was not investigated according to these standards [8,87,89,96,106,110–119]. In these papers specimen were prepared as notched or cracked for the initiation of crack. For fatigue tests; servo hydraulic test machines with approximately a load capacity of 5, 10 and 25 metric tons were used. All constant amplitude fatigue tests were conducted in tension–tension or tension–compression loading at a frequency of 10 Hz in lab-air at room temperature [9,87,89,108,106,117,118]. Beside this in some papers fatigue tests were conducted with sinusoidal waves of frequency 5 Hz [113,114]. During tests; the fatigue cracks were observed by various ways; charge coupled device (CCD) camera [110,115], visual observation [111], digital camera [112], clip gage [114], travelling optical microscope [106,116,119].

6.3. Tensile tests

The tensile behaviour of FMLs was generally investigated according to ASTM D3039 [93,99,105,107,120–126]. Beside this Kawai and Arai [123] were benefit from JIS K7073 standard for conducting tensile testing of FMLs. In all papers dealt with tensile properties of FMLs, the test specimen shapes and dimensions are different. Some of them used rectangular tensile specimens [6,106,121] and some of them used dog bone shape tensile specimens [101,109,118,124]. Beside this; there are a few papers that tensile test specimen dimensions were prepared according to the standards. In these papers; the authors were not referenced their tensile specimen dimensions. For tensile tests; universal and servo hydraulic testing machines were used: Instron tensile testing machines (4469, 1195, 8502, 4204, 1125, 1251) [96,105,107,109,120–122,127], MTS tensile testing machines (810, RT/50) [99,121,123–126] and Shimadzu tensile testing machine [121]. Tensile tests were performed at room temperature at various crosshead speeds of 0.1 mm/min [124], 0.5 mm/min [96], 1 mm/min [103,93,109,120,121,125,127], 1.27 mm/min [126], 2 mm/min [6,106,125,126], 5 mm/min [105]. However; in Carrillo and Cantwell's studies tensile behaviour of FMLs were investigated at a constant strain rate of 0.04 min\(^{-1}\) on an Instron 4204 universal test machine according to the ASTM D3039 test standard [107,122]. It is worthy to say that during tensile tests the Young's modulus of each specimen was recorded using a clip-on extensometer which was incapable of measuring the complete stress–strain curve.

6.4. Low and High velocity impact and blast loading tests

Due to the importance of understanding the dynamic loading effect on the FMLs, low and high velocity and also blast loading tests should be performed. According to the literature survey, it is well understood that there are many studies dealt with these test methods applied to the FMLs. Among these papers some of
them explain low velocity impact behaviour of FMLs [103,106,13,128,129], some of them dealt with high velocity impact performance of FMLs [13,128–131] and the others explain the blast loading effect on the FMLs [132–137].

6.4.1. Low velocity impact tests

First of all, the low velocity impact studies shall be mentioned. In these studies it is seen that all the low velocity impact tests were performed by drop weight impact tester. Tests were carried out using drop hammers that have various masses: 2000 g [103,106], 1160 g [128] and 575 g [13,129]. In addition to this, indenter types were chosen as similar (hemispherical) but the diameters are differing from each other as following: 5 mm [107], 10 mm [106], 12.7 mm [128], 15 mm [13,129]. For the investigation of low velocity impact performance; square FML samples were generally prepared as 75 mm × 75 mm, 100 mm × 100 mm, 125 mm × 125 mm and clamped between two square or circular frames. Square frames have 75 mm × 75 mm or 100 mm × 100 mm internal openings [106,128]. Beside this circular frames have internal diameters of 70 mm [107], 75 mm [103] and 80 mm [13]. The impact tests are instrumented as the contact force is measured with a load cell in the nose of the impactor and the strain in the specimen is measured with a strain gauge. After an impact, the carriage was caught in order to avoid secondary impacts.

6.4.2. High velocity impact tests

After an explanation about low velocity impact tests, in this section high velocity impact tests applied to FMLs shall be explained in detail. According to literature survey, it is very clear that generally a gas gun consisted of a pressure vessel was used for high velocity impact tests [13,128–131]. Generally square plates were clamped in a steel support square aperture so that the impactor can hit the centre of the test specimen. In this test method; after burning through a membrane of the gas gun, the expanding gas or air accelerates a projectile or a steel ball bearing to the velocities ranging between 25 and 100 m/s. The velocity of impactor prior to impact can be measured as it exited the barrel by the interruption of two laser beams a known distance apart by using light emitting diode photovoltaic cell pairs.

The ballistic limit is defined as the lowest velocity for complete penetration or perforation. Impact testing should be conducted over a range of impact energies until complete perforation of the FML target was achieved. The resulting perforation energy was then used to calculate the specific perforation energy of the target by normalizing the measured perforation energy by the areal density of the target [131]. After testing, the specimens could be sectioned, polished and then viewed under an optical microscope in order to elucidate the failure mechanisms during impact.

6.4.3. Blast loading tests

Numerous studies [132,134–138] have investigated the localized blast loading of FMLs. Blast loading was created using a plastic explosive (PE4) shaped into a circular disc and positioned at the centre of the plate, on top of a polystyrene foam (12–14 mm) pad to attenuate the blast. PE4 consists of 88% RDX and 12% lithium gum, has a detonation velocity of 8200 m/s and a TNT equivalency of 1.3 [132]. The detonator should be attached to the centre of the disc using 1 g of explosive, referred to as a ‘leader’. The impulse could be varied by varying the diameter of the explosive strips. The FML panels 300 mm × 300 mm [136], 400 mm × 400 mm [134,138] were clamped between two steel frames leaving an exposed area of 200 mm × 200 mm [132,136], 300 mm × 300 mm [134,135,138]. The frames were mounted onto a ballistic pendulum. Each FML panel should be weighted and the thickness should be measured at four different points before testing. After a blast; the swing of the pendulum could be used to calculate the impulse applied to the panel by detontating the explosive.

7. Conclusions

In this paper, historical development, advantages, disadvantages, production and applications of FMLs were presented by examining recent studies. In 1978 initial FMLs, ARALL laminates which consist alternating thin aluminum layers and aramid fibre prepreg were introduced. Later GLARE laminates based on high strength glass fibres and CARALL laminates based on carbon fibres were developed. GLARE laminates are the successor of ARALL laminates and commercially production of GLARE laminates were started in 1991. ARALL, GLARE and CARALL laminates are now being used as structural materials in aircrafts. Yet, it can be said that GLARE laminates found more use than ARALL and CARALL laminates in aircraft applications. Both laminates production involves five major activities; (i) surface treatment of metallic surface in order to improve bonding between metallic layer and fibre reinforced prepreg, (ii) material deposition, (iii) cure preparation, (iv) cure process, (v) post stretching for reducing residual stress of FML which caused by curing process. FMLs provide superior mechanical properties compared to fibre reinforced composites and aluminium alloys. High strength, high elasticity modulus with improved toughness and excellent fatigue properties can be said as major advantages of FMLs. ARALL, GLARE and CARALL laminates explained and compared with each other in following chapters.

In addition to the importance of reinforcement and matrix in polymer composites, the bonding between the composite laminae and the metallic layer is a key issue for the overall metal–fibre laminate performance. An adequate surface treatment of the metallic layer is required to assure a good mechanical and adhesive bond between the composite laminates and metal surfaces. In this paper the effects of surface treatments which are improved the metallic surface morphology for a better bonding with composite laminates are investigated. Surface treatment methods, such as mechanical, chemical, electrochemical, coupling agents and dry surface treatments are introduced and showed comparable performance to improve fibre metal laminates.

Mechanical properties of FMLs are being enhanced by the interface bond between composite and metal plies. This enhancement could be controlled by various test methods. This control reports give quality information and are suitable for design specifications. In this review; test methods of bending, fatigue, tensile, low and high velocity impact and blast loading tests for determining the mechanical properties of FMLs and research studies utilized from these test methods were explained in detail.

8. Developments for the future

FMLs consist of metallic alloy and fibre reinforced prepreg. Mostly commercially available GLARE, ARALL and CARALL consist various aluminium alloys. Many researches have been trying to use possible metallic alloys such as magnesium, titanium, etc. instead of aluminium alloys. It is expected that this diversity gives optimum mechanical properties. Same efforts have been examined for engineering polymeric materials to replace fibre reinforced prepreg.

Long processing cycle to cure the polymer matrix in the composite plies increases the cycle time of whole production and decreases productivity. New processing methods are investigated for improving the productivity of curing process and decreasing the labour costs of FMLs. These improvements will make FMLs very
attractive to various industrial applications (military, automotive and aircraft).

Last decades many researchers have been investigating the possibility of using thermoplastic materials instead of thermoset materials as matrix materials in FMLs. By using thermoplastic materials instead of thermoset materials, attractive to various industrial applications (military, automotive and aerospace industries). The development of FMLs has been driven by the need for lightweight, high-strength, and durable composite materials for aerospace and automotive applications. The use of thermoplastic materials offers several advantages over thermoset materials, including better processability, lower costs, and the ability to recycle.

References


