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Forming technology for composite/metal hybrids

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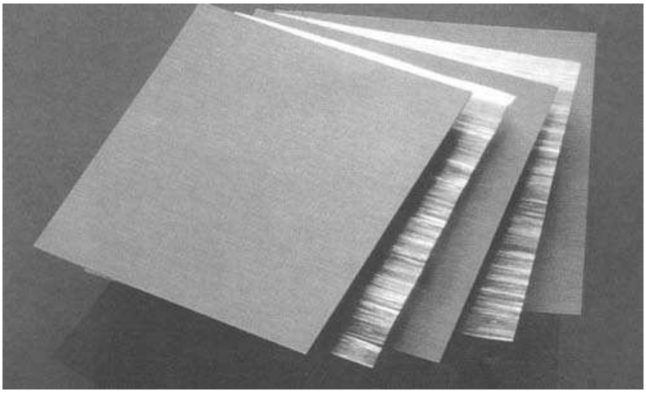
8.1 Introduction

Today, we are living in a multi-material society. This is true for consumer products, but also for engineering artefacts. Many structures are assembled from a selection of different materials. Materials for engineering purposes are, for example, metal alloys, composite materials, ceramics, and natural materials. These different materials are not only used side by side, at the level of structural elements, but also in mixed or so-called hybrid materials. Typical examples of hybrid materials are sandwich materials, metal matrix composites, and fibre metal laminates.

Ideas for new hybrid materials arise when one constituent alone cannot fulfil a specific set of requirements. Creating a hybrid material could be an option to solve this problem: by combining different materials, advantages of the constituents can be added and the new hybrid can comply with the intended objective. That does not imply that hybrid materials are super-materials, but that they have good to excellent values for a specific set of properties.

Sandwich materials, for example, offer a high bending stiffness in combination with a low weight. In addition, sandwich materials also have very good acoustic damping and thermal isolation properties. The sandwich concept involves a beam-like element with load carrying facings and a lightweight core for the shear loads and the support of the facings. When combined with high tensile fibres, the sandwich structures could be used for very specific applications, for which no other material (or combination of materials) is currently available. Typical examples are the ‘Voyager’ (1986), the first aircraft that flew non-stop around the world and the ‘Space Ship One’ winner of the X-price competition (2004). Both aircraft are designed and built by Scaled Composites of Burt Rutan (CEO). But also commercially available composite aircraft are made of sandwich materials, like the ‘Starship’ and the ‘Extra 400’.

Metal Matrix Composites are hybrid materials made of ceramic fibres or whiskers in a metal matrix. Examples of ceramic fibres are alumina or silicon carbide fibres, and the matrix is often a metal alloy with a rather low melting



8.1 The FML-concept: a 3/2 lay-up of a fibre metal laminate (three layers of metal alloy and two layers of composite – each composite layer consisting of two to four prepreg layers).

point like magnesium or aluminium alloys. The combination of these materials offers engineering materials with good mechanical properties at elevated temperatures, up to 400ºC. Typical MMC-applications are engine parts and parts subjected to excessive wear.

The last examples to be mentioned here are the fibre metal laminates (FML). These laminates have been developed for their excellent damage tolerance properties, such as fatigue resistance, residual strength, and impact resistance. These laminates consist of alternating layers of thin metal sheet and composite layers (see Fig. 8.1). Current applications of these laminates are fuselage panels of the Airbus A380, leading edges of the tail planes of the A380, and blast-resistant containers.

In this chapter an overview is presented about the forming technology of composite/metal hybrids, in particular the fibre metal laminates (FML). The main reason for this focus is that sandwich materials, based on thermoset materials, deform elastically only, and MMC are generally cast. A second reason is that FML offer a good example to illustrate the typical phenomena of hybrids.

In the second section a brief outline will be given about the development of FML, followed by a section about the properties of these laminates. In Sections 8.4 and 8.5 the appropriate forming processes and the modelling of these processes are described. The last two sections give some concluding remarks and references.

8.2 Development of composite/metal hybrids

The different hybrids consisting of composite and metal constituents have their own history. This is illustrated by a brief description of the development of the sandwich concept, and a more extensive one about the development of fibre metal laminates.

8.2.1 Sandwich materials[1,2]

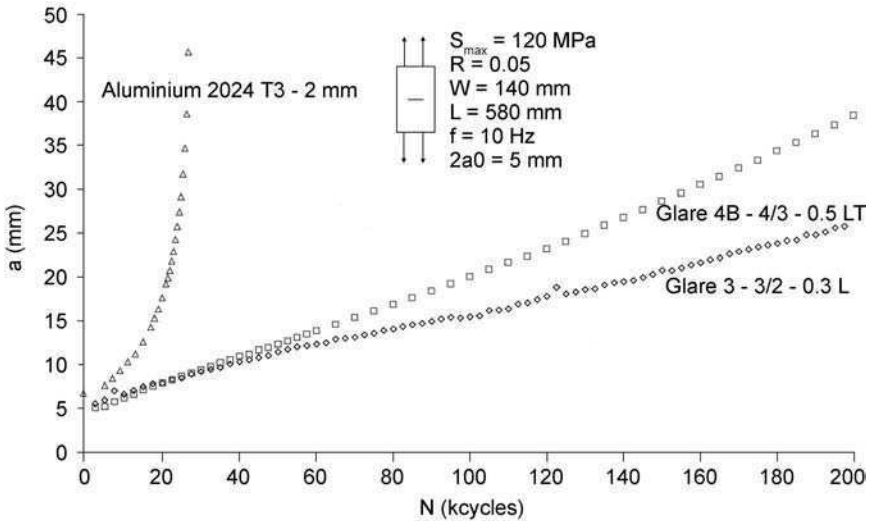
The concept of sandwich materials has been known since the middle of the 19th century. The first published example was a bridge, built in 1846 in Wales, for which sandwich-like structural elements were used. These elements were made of steel faces and wooden core materials riveted together. Later, in Germany as well as in England, new sandwich materials were developed. The main reason for this development was obtaining lightweight structures with a high bending stiffness. In 1943 the honeycomb structure was invented, so after the Second World War there was a wide variety of possible material combinations: face sheets made of metal alloys, composites and plastics, and core materials made of Balsa wood, synthetic foams, honeycomb, etc. Among the most commonly used sandwich materials are the ones with composite facings and metal (aluminium) honeycomb, used in space structures, and sandwiches made of metal facings and a synthetic foam or honeycomb, used in aircraft structures. However, the sandwich concept is most widespread in full composites, with composite facings and a foam or honeycomb for the core (no metallic constituents).

8.2.2 Overview of the development of FML[3]

The history of FML starts with the bonding technology Fokker applied on their F-27 aircraft launched in 1955. The main reasons for the introduction of bonded structures were costs (related to lack of investment capital) and structural stability. But the layered structures also offered another advantage: bonded structures had significantly better fatigue resistance. In the following decades the bonding technology was further developed. One of the items of that research was that Fokker tried to improve the fatigue resistance by applying fibres in the bond layers. The fatigue resistance was further improved but not significantly and Fokker stopped further research. Other reasons were that Fokker had no new aircraft where they could apply the new material, and replacing existing materials was too expensive.

The Technical University of Delft continued the research in the late 1970s, and started changing the materials and the thickness of the layers. The reduction of metal layer thickness, in particular, resulted in a big improvement of the fatigue resistance (see Fig. 8.2).

In 1979 the first prototype of a fibre metal laminate was tested at the University. This laminate was named ARALL: *AR*amid *AL*uminium *L*aminate, and was based on aramid fibres. From the early 1980s onwards, the research on the laminates expanded and some industries showed their interest. Companies like ALCOA (US) and AKZO (NL) sponsored the research. The first large application came with the cargo-door of the C17 military transport aircraft. The door performed well but later a metal one replaced it since the ARALL-door was too expensive.



8.2 Comparison of the fatigue crack growth curves between the monolithic aluminium alloy 2024-T3 and GLARE 3. Note: until the 1990s, 2024-T3 had been the baseline alloy for aircraft fuselages; it was the best choice with respect to fatigue resistance.

In 1986 research started on a second FML-variant: GLARE, based on glass fibres. The main reason to switch to glass fibres was that the aramid fibres failed under particular loading conditions. But fibre failure is unacceptable: the fatigue resistance relies on the mechanism of crack bridging. The glass fibres in GLARE do not have this disadvantage, and therefore GLARE became the most important FML-type. During the development of GLARE another big problem was solved. By so-called ‘splicing’ of the metal layers, very large skin panels could be manufactured without (riveted) joints. In the ARALL- period the laminates were treated as metal sheets: first, flat laminates were manufactured which were subsequently formed and joined to larger structures. For GLARE, however, the laminates were made like composites: the large skins (and reinforcements) are made by lay-up processes.

In the early 1990s Airbus Industry started a design study for a very large aircraft. This aircraft should complete the ‘family of aircraft’ offered to customers. After a lot of market and feasibility studies, the final design took shape around 1996 and was called ‘A3XX’. At the same time GLARE was mature enough to be regarded as a potential candidate for the fuselage of this aircraft. After discussions with Airbus, the research in Holland (University of Delft, the National Aerospace Laboratory and Stork Fokker) increased significantly. The government was willing to support this basic research, which had the objective to make GLARE ready for application in full-size structures. As the final result of this process the GLARE laminates are applied on significant parts of the A380 fuselage (large front and aft sections). Stork Fokker produces most of these skin panels in a specially built factory. Besides the fuselage panels GLARE laminates are also applied in the leading edges of the vertical and horizontal tail planes of the A380.

8.3 Properties of fibre metal laminates

8.3.1 Mechanical properties

The mechanical properties of fibre metal laminates (FML) depend on the constituents of the laminates: the fibres, the metal alloy, and the adhesive or resin. The properties of the fibres and the metal alloy are dominant for most properties like strength and stiffness. The properties of the adhesive are important only in the laminate properties in which a shear component is involved. A typical example is the interlaminar shear strength (ILSS).

The laminates are anisotropic or orthotropic, depending on their composition. Therefore, as a result the in-plane mechanical properties are presented for the longitudinal (L) direction (parallel to the rolling direction of the metal layers) and the long-transverse (LT) direction (in plane but perpendicular to the rolling direction). For an A-version of a particular laminate the (main) fibre direction and the rolling direction coincide; for a B-version the (main) fibre direction and rolling direction are perpendicular to each other.

Tension test

In Table 8.1 the most important mechanical properties for a few FML-types are presented, with the values of aluminium alloys for comparison. In the following text a few comments are made about these properties.

The Young's modulus or elastic modulus (E) depends on the fibre directions: this is obvious for the GLARE-2 laminate, which only has fibres in L-direction. GLARE-3 is a cross-ply laminate with 50% of the fibres in L-direction and 50% of the fibres in LT-direction and the E-modulus in L- and LT-directions for GLARE-3 laminates is equal. The metal alloys, the fibres, and their respective volumes determine the magnitude of the E-modulus. The classic rule of mixtures that is used for full composites can also be applied for FML.

The yield stress (σ_y) is dictated by the metal alloys, which is the only constituent with plastic yielding. The value of the yield stress, however, is also influenced by the fibres, by the stiffness of the fibres and the fibre content of the laminate. The ultimate tensile stress (σ_{ult}) is dictated by the failure of the fibres. Fibres deform elastically until failure. The failure of the fibres is abrupt and accompanied by a significant release of energy, causing fracture and delamination of a significant part of the specimen.

The fibres also dominate the failure strain (ϵ_f) of the laminate. When fibres

Table 8.1 Mechanical properties for some GLARE-laminates and some aluminium alloys

Property	Sym	Dir	Dim	GLARE-1	GLARE-2	GLARE-3	2024-T3	7475-T6
Young's modulus	E	L	GPa	65	66	57.5	72.5	71
		LT		49	50	57.5	72.5	71
Yield stress	σ_y	L	MPa	550	400	320	324	483
		LT		340	230	320	290	469
Ultimate tensile stress	σ_{ult}	L	MPa	1300	1230	755	440	538
		LT		360	320	755	435	538
Failure strain	ϵ	L	%	4.5	5	5	13.6	8
		LT		7.5	13.5	5	13.6	8

Sym = symbol
Dir = orientation/direction
Dim = dimension
GLARE-1: UD laminate; Al-7475-T6 alloy
GLARE-2: UD laminate; Al-2024-T3 alloy
GLARE-3: CP-laminate (50/50); Al-2024-T3 alloy

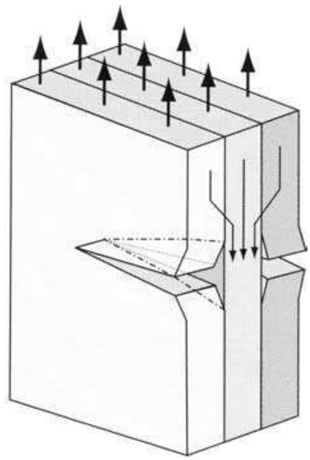
are running in loading direction the failure strain of the laminate is equal to the (small) failure strain of the fibres, which is in the range of 1–5%, depending on the fibre system. Only for UD-laminates with fibres in one direction (L-direction) the failure strain in LT-direction is somewhat larger, and comparable to the failure strain of the metal alloy.

The strain hardening beyond the yield stress is almost linear. Since the fibres continue to deform elastically, their contribution to the stress, once the metal alloy yields, is significant. As a result, the stress-strain relation beyond the yield point is almost linear, which results in a typical bilinear stress-strain curve.

Fatigue

The high fatigue resistance is the most important property of FML. In Fig. 8.2 crack growth curves are presented for GLARE-3 and aluminium 2024-T3. From that figure it is obvious that the crack growth rate in FML is much smaller. For aluminium alloys about 80–90% of the total fatigue life is required for crack initiation, and about 10–20% for crack growth. Once a crack is initiated, the crack grows relatively fast. For FML it is the opposite: about 10–20% (or less) of the fatigue life is related to crack initiation, and about 80–90% to crack growth. The number of cycles to initiate a fatigue crack in both aluminium and FML is comparable.

The slow crack growth in FML is caused by a mechanism called 'fibre bridging' (see Fig. 8.3). The metal layers may have fatigue cracks, but the fibre



8.3 Schematic presentation of the crack bridging mechanism in FML.

layers stay intact, bridging the crack. The fibres bypass the stresses of the cracked aluminium layers, whereas in monolithic aluminium the stresses have to 'flow' around the crack tip. In the latter case the stress intensity at the crack tip and the crack growth rate increase significantly. An essential part for the crack bridging is the local delamination of the fibre and metal layers. For a slow crack growth there should be a good balance between the crack size, the delamination and the properties of the constituents.[4]

Residual strength

The residual strength of a material is the remaining strength, when damage is present in the material. In general, this property is tested using sheet specimen with a specified damage to it (e.g., a saw-cut of specific length). FML have high residual strength values when compared with aluminium alloys. Again the main reason is the crack bridging by the fibres. When the damage is caused by fatigue, the crack bridging is maximised; when the fibres are cut by the damage source, some crack bridging will still occur during the stable crack extension preceding the final failure.[5]

Impact and blast resistance

The combination of metal plasticity and a high strain hardening, which is facilitated by the fibres, also give the FML high impact and blast resistance. In particular, the blast resistance is high, since a large portion of the plastic deformation capacity of the material is used in applications like the bomb-proof luggage container that is made by ECOS (US).

8.3.2 Some physical properties

Density

The density of the laminates depends on the constituents and composition of the laminates. The density of FML is usually smaller than the density of the related metal alloy. By adding composite layers, which have densities in the range of 1.5–2.0 kg/dm^3, the overall density of, e.g., GLARE is about 10% lower than for the aluminium alloys.

Electric and magnetic properties

The electric and magnetic properties of a laminate are related to its constituents: often, metal alloys are good electrical conductors, but polymers are not. For the fibres: the aramid and glass fibres have poor conductive properties, but carbon fibres are good conductors. So, depending on the combination of metal alloys, fibres, and polymers, the laminates can have a wide range of different characteristics. In addition, the in-plane properties are often much different from the properties in thickness direction, where the composite layers may act as barriers.

Internal stresses

FML are made by alternating metal sheets and prepreg layers. The layers are stacked, sealed in a vacuum bag and cured in an autoclave at elevated temperature and high pressure. The temperature depends on the polymer that is used as matrix material. Most resins for GLARE-type laminates are toughened epoxies, and have curing temperatures of about 100–150ºC. Curing different materials at these temperatures causes internal stresses, since the coefficients of thermal expansion differ. Therefore, in a GLARE laminate, after curing the aluminium layers are in tension and the composite layers are in compression. The magnitude of these residual stresses depend on the thermal properties, the composition, the number and thickness of the layers, fibre orientations, etc. Typical values are 10–30 MPa (tension) for the metal layers and 40–80 MPa (compression) for the composite layers.

Due to their composition FML offer excellent resistance to flames, corrosion, etc. The alternating layers protect each other and penetration of flames, moisture, etc., is very difficult because of the thickness. This is explained in the following two examples.

Fire resistance[6]

FML do have good fire resistance, in particular the thicker laminates (4/3-lay-up and larger). When conventional aluminium alloys are exposed to flames, the flame penetrates the sheet in a very short time (less than two minutes). FML based on aluminium sheets require a much larger time before flames penetrate through the laminate (in the order of 10–15 minutes). The reason is that the composite layers carbonise and delaminate, thereby shielding the heat from inside layers. At the same time the aluminium, due to its conductivity, dissipates the heat over a large area.

Corrosion resistance[7]

Another protection mechanism is active when the laminate is exposed to moisture. In metal alloys this will result in corrosion: the metal dissolves locally, and pits and holes arise in the metal. In FML, the composite layers stops further corrosion attack, and the corrosion is limited to the outside metal layer. On the other hand, the metal layers protect the composite layers. These layers can deteriorate under the influence of ultraviolet radiation and moisture. Metal layers cover the composite layers (except for the edges), and therefore, there is almost no deterioration of the composite layers. Only minimum moisture ingress is possible via the edges.

8.4 Production processes for fibre metal laminates

Production processes for hybrids are related to the properties of the constituents. In this section both machining and forming processes are described, with emphasis on the forming processes. Many production processes have a resemblance to either metal or composite production processes.

8.4.1 Cutting processes for FML

Cutting of FML is not too difficult, but the constituents and the composition of the laminates require procedures different from the cutting of metal alloys or composites. For cutting of FML, the following issues should be kept in mind:

- The highly abrasive fibres cause rapid tool wear, unless specific tooling materials are used. This is true for glass and carbon fibres. For aramid fibres wear resistant tooling is also required, but for another reason. The aramid fibre is neither hard nor abrasive, but very tough, and only sharp cutting edges are able to cut these fibres.
- Dull cutting tools, due to tool wear, produce heat. This heat can affect the laminate, and is specifically detrimental to the laminate causing delaminations and/or matrix damage.
- Forces perpendicular to the laminates may cause delaminations. These forces act perpendicular to the interfaces between the different layers, and should be controlled carefully. Part of this control is the limitation of tool wear, since

the decreasing effectiveness of wearing cutting tools is often compensated with an increase in the cutting force.

These problems are related to the wear of the tool bit; therefore, adapting the tool material to the resist the wear is a very important measure. Tests have revealed that tool bits made of solid cemented carbide/hard metal (HM) or poly crystal diamond (PCD) tipped tool bits offer the best solutions. Unfortunately, these tool bits are also brittle so they can only be used in stable machines. For manual operations, a combination of a tough HSS tool body and HM or PCD cutting edges is required.

Some cutting processes, such as (abrasive) water jet cutting or laser jet cutting, are not in contact with the laminate. Abrasive water jet cutting is used for cutting edges or making cutouts, although the latter is more complicated. The edge quality is not very high: the edge has a sandy appearance, which is not acceptable in every application. The laser jet cutting introduces a small heat-affected zone in the laminates: a zone in which the condition of the metal alloy has been changed and where the matrix material is damaged. Despite the fact that this zone is very small, for aerospace applications, the existence of this zone is not acceptable.

Cutting takes place prior to a forming process and after a forming or lay-up process. For the cutting prior to the forming process no close tolerances are required, but for the cutting or trimming after the forming or lay-up process, the tolerances and edge qualities are high. This will influence the selection of the cutting process. Some common cutting processes for FML are discussed below.

Shearing

Shearing is a process used for rough blanking of metal sheets or blanks used in subsequent forming processes. The mechanism of this process is based on indentation and shearing of the material in its thickness direction. Typical processes applying this principle are punching, shearing and slitting. FML can also be sheared but the allowable thickness of the laminate is limited. The main reason is the high local forces, which increase with increasing thickness, and result in delaminations.

Routing or edge milling

The most common process to machine the edges of sheet materials is routing. In this process a simple mill trims the laminate to the right dimensions. Routing does not cause any problems when sharp and wear-resistant tool bits are used. When the tool bit becomes dull, the chips and debris can be pushed between the layers of the laminate. An additional requirement for routing is that the helix angle of the tool should be small, otherwise the top layer of the laminate is peeled off. Alternative processes for routing are the water and laser jet-cutting processes. As stated before the edge quality for these processes is not as high as for a milling process.

Drilling

Most structures are made by joining structural elements like shells, skins, beams, and profiles. A favourable joining method is mechanical fastening, using rivets or bolts. When this joining technique is selected, holes should be drilled in the structural elements. As for the other cutting processes, the drill bits should be sharp and remain sharp. When the drill bit is sharp, the feed force, perpendicular to the laminate, is small. A small feed force is necessary to prevent the delamination of the layers. As for routing, the helix angle of the drill bit is important: that angle should not be too large, in order to prevent delamination (peeling) of the top layer.

8.4.2 Formability aspects of FML

In-plane deformations

Metal alloys can be deformed plastically and the failure strain is usually in the order of 10–50%. Metal alloys also exhibit some elastic deformation, resulting in spring back, residual stresses, or a combination of the two. The achievable combinations of strains are large; they can be decomposed in in-plane tensile strains, in-plane compressive strains, in-plane shear strains, bending deformations, etc.

Composite layers have a very limited formability. The failure strain of the fibres is small: from 1% for carbon fibres, and 2–2.5% for aramid fibres up to 4–5% for glass fibres. The deformation of fibres is pure elastic, so after deforming, the fibres cause some kind of spring back. The failure strain of the matrix or resin in a prepreg is limited, too, in particular for thermoset polymers. In addition, the embedded fibres create stress concentrations in the matrix, further reducing the failure strain. Thermoplastic matrix materials offer a (much) larger failure strain, but the high glass-transition temperature T_g, causes high internal stresses (see Section 8.3.2).

The laminates can be divided in two groups: uni-directional (UD) laminates, all fibres are placed in one direction, and laminates with fibres in two orthogonal directions, cross ply (CP) laminates. UD-laminates are applied in profiles like stringers. These prismatic elements are bent with the fibres running in longitudinal direction. In that case the fibres are not deformed, and the small failure strain of the fibre does not limit the deformations. In case of CP-laminates, the stretching and bending in fibre directions is severely limited by the limited strain of the fibres. The only way to have some deformation capability is stretching in the bias-directions of the laminate. In that case the so-called 'trellis-effect' is activated.

Bending

Deformations in FML are also influenced by the lay-up of the laminates. Thin laminates are bent easily: the distance of the deforming fibres to the neutral axis is small. For a 2/1 lay-up the fibres are at the neutral axis and for a 3/2-lay-up the distance of the fibres to the neutral axis is still quite small. Depending on the fibre orientation (UD-laminates are favourable for bending) the minimum bend radius increases with increasing thickness. When fibres are loaded during bending, the minimum bend radius increases exponentially, and the minimum bend radius is a function of the (small) failure strain of the fibres:

$$r_{min} \approx t/2\epsilon \qquad 8.1$$

where t is the distance of the most outer fibres layers to the centre line and ϵ the failure strain of the fibres.

When the fibres are parallel to the bend line (no fibre deformations) the increase of the minimum bend radius is comparable to metal alloys. However, for thicker laminates (1.5–2.0 mm and larger), the failure mode changes from fracture of the outer surface to delamination of the interfaces just outside the bend zone. Once the delamination is the dominant fracture mode, a rapid increase in the minimum bend radius/thickness ratio is the result.

Elastic recovery

When FML are deformed into structural elements, part of the applied work is elastic. This elastic energy causes spring back, residual stresses, or a combination of these two. For bending of profiles or flanges the spring back dominates; for shallow three dimensional shapes, the largest part of the elastic energy is stored as residual stresses. FML often show larger spring back angles or residual stresses than (reference) metal alloys. The main reason is the elastic energy, which is absorbed by the fibres that deform elastically only.

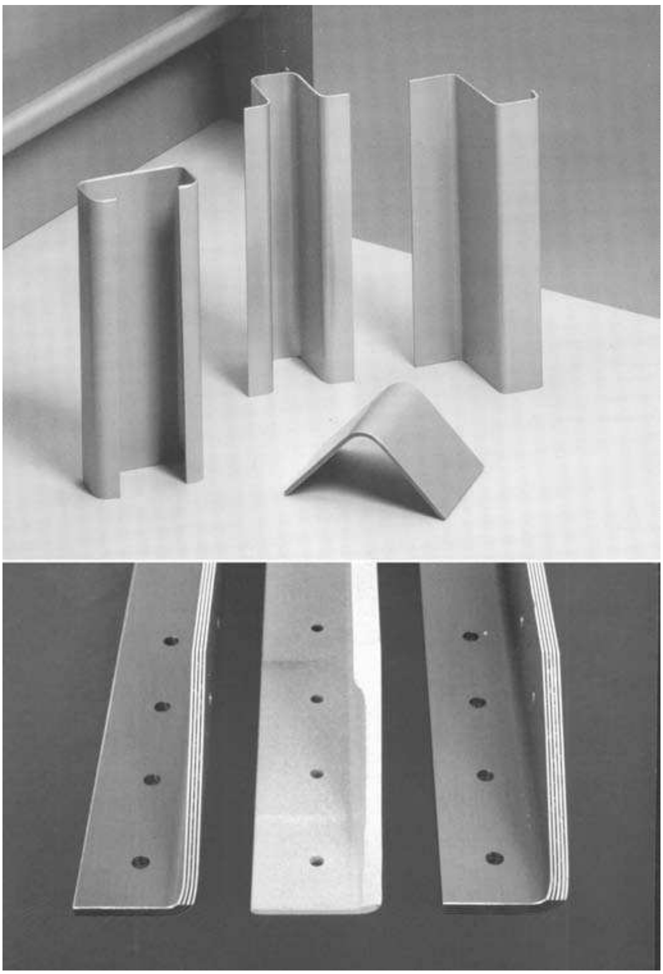
8.4.3 Forming processes for FML

For the manufacture of FML parts conventional metal forming processes are suitable options. This is true for small to medium-size parts like profiles, beams, clips and cleats. For large-size shells like the skins of aircraft wings and fuselages the lay-up technology is more appropriate (see next section). These shells are too large to be formed on conventional equipment and the formability of the laminates is insufficient. In this section some forming processes are described briefly. In this overview a distinction is made between processes for laminates and processes for the forming of individual layers, before being processed in lay-up and curing processes.

The following processes are in use or their feasibility has been demonstrated: press brake bending, roll bending, roll forming of profiles, press forming and stretch forming.

Press brake bending

The bending of profiles with a press brake is similar to the bending of metal profiles. Since the fibres are parallel to the bend line, the metal constituent dominates the minimum bend radius and spring back angles for thin laminates (up to 1.5–2.0 mm) (see Fig. 8.4 for examples). For the bending of thicker laminates, the bend radius increases rapidly as discussed in Section 8.4.2. One option to manufacture thick profiles is to assemble preformed profiles in a subsequent bonding step (see Fig. 8.4). Applying this method very small bend radius/thickness ratios are achievable. However, for this option the design freedom of the profile geometry decreases.



8.4 Some examples of profiles made by press brake bending (top) and two examples of thick stringers made by bending and bonding of several profiles, bottom left and right (the stringer in the center is a machined stringer).

Roll bending

The roll bending of laminates can be used to create a single curvature in a shell or skin. Due to roll bending some internal stresses are introduced and the spring back requires multiple passes through the set of rolls to obtain the final radius. Currently, lay-up techniques are used for the manufacture of single curved shells.

Roll forming of profiles

Roll forming is a forming process for the manufacture of symmetrical profiles from strip. It has been demonstrated that this process is feasible for thin laminates, but the investment costs for the tooling are high.

Press forming

The applicability of press forming processes like rubber forming is limited. The main reason is that in-plane deformations for FML are limited by the failure strains of the fibres (depending of the fibre system: 1–5%). Only shallow shapes can be press formed like stiffening beads used in web plates or panels. The manufacture of curved flanges is not really feasible: for shrink flanges the laminates wrinkle and delaminate, and for stretch flanges the strain is limited by the maximum strain for the fibres and the complicated spring back compensation for the tools.

Stretch forming

Finally, the use of the stretch-forming process is also limited. When the stretching forces are applied in one of the fibre directions, the maximum achievable strain is small and there will be significant spring back. The best option is to stretch form these laminates in bias-direction, activating the trellis-effect in the composite layers. However, this is only valid for applications where the fibre orientation is of minor importance such as for impact-dominated shells (leading edges of wings, cockpit and canopy).

A second option for the manufacture of FML-parts is first to form the metal layers and to assemble them into laminate, applying a subsequent lay-up and curing cycle. The forming of the thin metal layers is a delicate process, due to the small thickness of the layers; the layers may buckle and wrinkle. If possible, the layers should be formed in stacks, because then the layers can support each other, it reduces the number of forming operations, and it improves the matching of the layers. A few manufacturing processes are tried to demonstrate this production route.

Roll forming

The roll forming process for the manufacture of profiles is used for stacks of metal and prepreg layers (uncured laminates). The stack is prepared, then roll formed into the required shape and cured after the forming operation. The matching of the layers is perfect and the spring back and residual stresses are very small. However, the thickness in the radii of the profiles might not be constant due to some resin squeeze out from the composite layers during roll forming.

Stretch forming

For the manufacture of slightly double curved panels it is possible to stretch form several metal layers in one cycle. The benefits of this route are the increase of the formability limits (further increase is possible using heat treatments), and the minimisation of residual stresses and spring back; a drawback is the surface treatments that have to be applied to double curved sheets.

Press forming (of metal layers)

The press forming for individual layers was demonstrated in the JSF-program. In this program a prototype of a weapon bay door was manufactured. These doors consisted of two skin panels and an inner structure. One skin panel is almost flat and the other skin panel has a deep drawn shape. Rubber forming of the metal layers followed by film infusion process of the fibre reinforcement and curing in an autoclave made the latter skin panel. This manufacturing procedure was applied successfully.

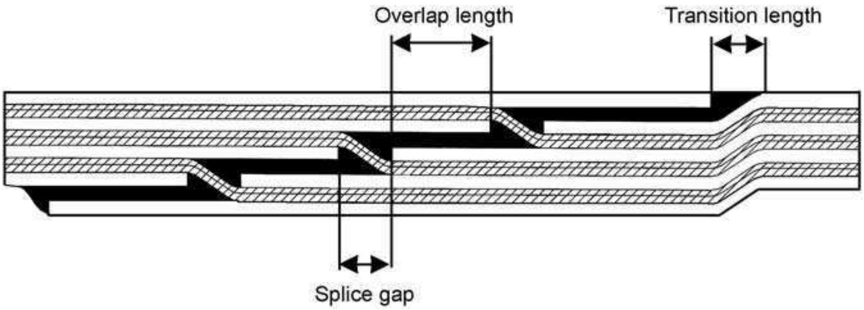
Resin infusion

The last issue for this production route is about the application of the composite layers prior to the curing cycle. There are several ways to place the composite layers. One method is the lay-up of prepreg, but also infusion processes like resin infusion and film infusion of dry fabrics are feasible. Which method is the best, depends on the specified fibre architecture and the applied polymers.

8.4.4 Lay-up techniques for FML shells

Large size FML shells cannot be made by forming processes, but are made by lay-up processes, which are related to the manufacturing of composites.

The lay-up processes are used for large single or slightly double curved shells, like skin panels for aircraft structures, such as the Airbus A380. The benefits of lay-up processes are the size of the skin panel, which is only limited



8.5 The configuration of an overlap splice.

by the autoclave (not by the dimensions of the raw materials), and the lay-up of (local) details, which makes the panel an integral part. For example: during the lay-up of the fuselage skin panels of the Airbus A380 additional layers, so-called doublers are added to reinforce the panel. Typical areas for these doublers are the window belt area and the door areas.

The fact that the size of the autoclave determines the panel size is common for composites, but is not obvious for FML. Since the width of metal sheets is limited, splices (see Fig. 8.5) are required to make larger panels. A splice is a kind of bonded joint made during the lay-up process. The discontinuity in the individual layers is placed at different locations. The best option used today is the overlap splice. The overlap gives only a small increase in laminate thickness, but is very cost-effective since no close lay-up tolerances are required.

Single curved laminates

Fuselage skin panels and leading edges of wings are typical examples of single curved shells. These laminates are curved in one direction, which means that during the lay-up process the metal sheets are subjected to bending deformations but not to in-plane deformations. Since the sheets are thin (0.2–0.5 mm) the forces required to place the sheets in the curved moulds are negligible; the same is true for the prepreg layers.

During the lay-up of the panels, splices are made in the panels if the panel dimensions are larger than the width of the metal sheets. The splices can be oriented in length or width direction.

Double curved laminates

Besides single curved panels, fuselages also have double curved shells: shells with smooth curvatures in two orthogonal directions. The lay-up of the composite layers is easy: the prepreg layers are flexible and more or less pliable. The lay-up of the metal layers is much more difficult. The sheets have to match the double curvature of the lay-up tool and this is only feasible by elastic in-plane deformations. To force the sheet in the mould, relatively high autoclave pressures are needed. Once the pressure is applied internal stresses exist in the metal sheet: compressive stresses at the edges and tension stresses in the centre of the sheet. The magnitude of these stresses is related to the width of the sheet; the smaller the width the smaller the stresses. When a sheet becomes too wide, the pressure is not sufficient to suppress the wrinkling at the edges and the sheet width should be decreased. The applicable width of a metal sheet in a double curved panel also depends on the curvatures or bend radii. The elastic stresses contribute to the spring back of the panel after curing.

8.5 Modelling of FML

The modelling of the behaviour of FML and in particular modelling of forming processes does not have a long tradition yet. Therefore, no extensive experience of modelling can be presented in this section. The main focus thus far has been on the modelling of the mechanical behaviour of laminates. Special interest has been in the modelling of fatigue behaviour and the failure of FML under different loading conditions. For some topics finite element models, for others, analytical models are developed. The main objective for the model development is to give the designers, who apply the materials in aircraft structures, the necessary tools for designing with FML. Some models are developed for particular forming processes, like bending.

In this section a brief overview is given of the efforts of the modelling of FML.

8.5.1 Analytical modelling of mechanical properties

Classic laminate theory

For a first approximation of the elastic properties the classic laminate theory (CLT) can be used, just as for composite materials. In general the FML are orthotropic laminates with one or two fibre directions. The properties in 1- and 2-directions can be calculated using the properties of the constituents, the metal alloy and the fibre composite or prepreg. Other simple rules that can be applied for FML are the Rules of Mixtures (RoM).

Once the material properties in the plastic area have to be calculated, the plasticity of the metal layers becomes important. There are several options to model this behaviour. The first option is: the stress strain curve beyond the yield stress is assumed to be a linear relationship, by neglecting the strain hardening of the metal. The strain hardening of the metal is small compared to the stress increase in the composite layers. The limit of the stress-strain curve is the failure strain of the fibres. A second option, by a much more complex approach, involves the strain hardening behaviour of the metal alloy. In that case special algorithms are required to calculate the stress-strain curve.

In these methods the implementation of the residual stress system further increases the complexity of the required formulas due to the curing process.

The MVF approach[8]

A simple tool for designers to calculate some basic properties is the 'metal volume fraction' (MVF) approach. This MVF represents the relative metal contribution in a FML and is defined as:

$$\mathrm{MVF} = (\Sigma\, t_{\mathrm{metal}})/t_{\mathrm{lam}} \qquad 8.2$$

where t_{metal} is the thickness of one metal layer; t_{lam} the thickness of the laminate)

The MVF approach is based on a linear relationship between the material properties at MVF = 1, which represents a pure metal, and MVF = 0, which represents the property of the composite layer. Tests revealed that the MVF method is applicable between 0.45 < MVF < 0.85. FML like GLARE and ARALL have a MVF in this range. The accuracy of this tool is about five percent. When a knockdown factor of 1.1 is applied to the final result, the MVF-tool results are safe and slightly conservative. During the development of GLARE the airworthiness authorities accepted this approach for several typical material properties like tensile strength, compression strength, bearing strength, and blunt notch strength.

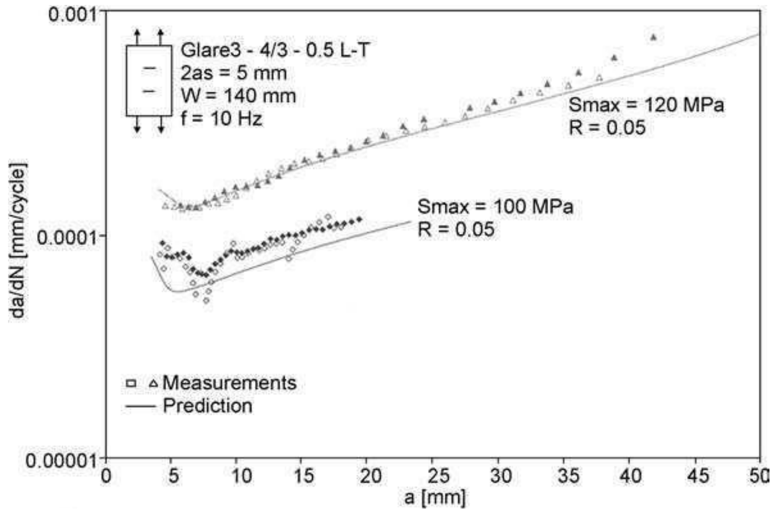
Stress intensity factors for fatigue

Alderliesten[4] proved that an extension to the classical theory of stress intensity factors, as used for the fatigue in metal structures, could also be applied for FML. In his model the stress intensity at the tip is the superposition of the far field stress intensity and a (negative) stress intensity caused by the fibre bridging:

$$K_{\mathrm{tip}} = K_{\mathrm{far\ field}} + K_{\mathrm{bridging}} \qquad 8.3$$

Since the fibre bridging stress is dependent on the delamination, the K_{tip} and K_{bridging} values also depend on the delamination sizes and delamination shapes. Based on a range of tests, the delamination growth has been modelled using a Paris-type equation for the energy release during delamination. Using this equation the delamination growth results are related to the crack opening, the crack growth, and the bridging stresses, which are in balance with each other.

Comparing test data, for through cracks under constant amplitude loading, with the numerical results shows good results for the crack growth in different FML (for an example see Fig. 8.6). A step further would be to apply a similar approach to fatigue of FML with a part-through crack.



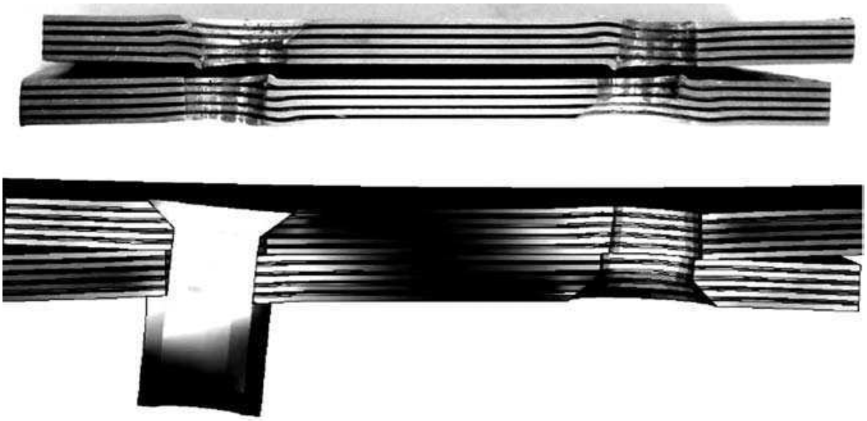
8.6 Experimental and numerical data for the fatigue crack growth of FML under constant amplitude loading and through cracks.[4]

8.5.2 FE modelling of FML structures

FE-codes are also used for numerical stress calculations of FML structures. For the modelling of the FML there are several options.

The first option is to calculate the laminate properties for every section of the structure. As stated before, FML skins are often reinforced locally with doublers, and the lay-up of the skin can change, depending on the applied loads. Thus the laminate can be tailored by adding or removing layers, and/or by changing fibre orientations. For stress analysis of aircraft structures the required composition is determined for each 'bay': a section confined by two stringers and two frames (bay-size is in the order of 200 × 500 mm). For that section, the laminate properties can be calculated by the classic laminate theory or by the MVF approach. The laminate properties are used during the optimisation of the structure. When the structure has to be adapted, new laminate properties for the sections involved are supplied.

FE-models can also use more sophisticated modelling: the different layers of the laminate are modelled, and each layer has its material model. This type of model requires additional modelling features such as the modelling of the interfaces between the layers. Since the number of elements and the computation time will increase significantly, this modelling is not applied to large or full-size structures, but to structural details only. Current models are very accurate in predicting, e.g., failure of riveted joints (see Fig. 8.7).



8.7 A riveted joint, tested (top) and modelled (bottom). The model ABAQUS was used; the layers were modelled individually.

8.5.3 Modelling of forming processes[9]

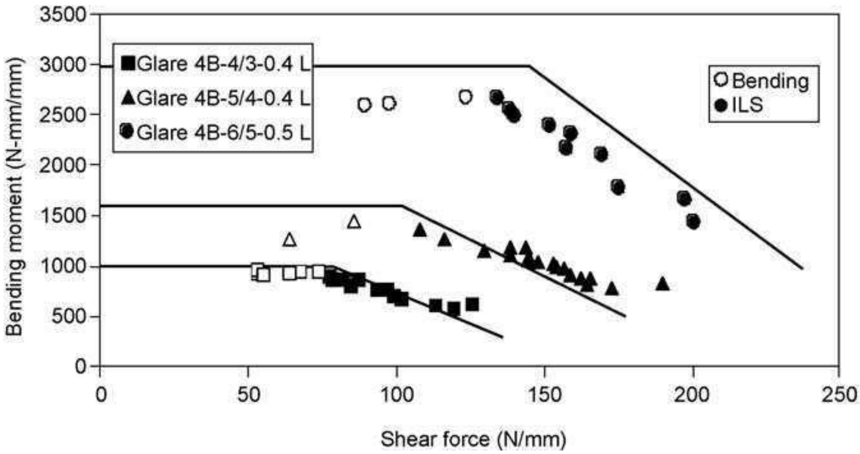
FML are hybrid laminates made of composite layers and metal layers. Due to the plasticity of the metal layers, it is possible to give the laminates some permanent deformations. In Section 8.4.2 the formability aspects of FML were discussed, which can be summarised as: small permanent deformations in fibre directions, somewhat larger failure strains perpendicular to the fibres, and often a significant elastic recovery after forming, either by means of spring back or internal stresses.

In-plane deformations

The applicable in-plane deformations are very small and deep drawing operations cannot be applied. Only some limited stretching is feasible, in particular when the laminates are not directly stretched in the fibre directions but at an off-axis angle (e.g., in bias-directions). In that case the principle of the forming limit curve (FLC) can be used to predict the failure of the laminate. This curve presents the forming limits, e.g. expressed in strains for in-plane strain combinations. For that case the limits in fibre directions are set by the failure strains of the fibres.

Bending

For the manufacture of FML profiles the cheapest method is to bend prefabricated laminates. However, the minimum bend radii for bending laminates depend primarily on the fibre orientation and the number of layers. A model has been developed to evaluate the manufacturability of a particular



8.8 Forming limits expressed in maximum applicable combination of bending moment and shear forces for different FML.[9]

laminate/radius combination. This model deviates from elastic models in the sense that plastic behaviour is incorporated. Also the shear stresses and strains in thickness directions cannot be neglected, which makes the modelling rather complex. An important parameter in bending of FML is the transverse shear stress, which should be equal at both sides at each interface. This results in different values for the transverse shear strain (since the materials properties are different), and subsequently straight cross sections does not remain straight during bending. During research several models for the local shear stresses have been investigated. The ultimate result of the model is related to a plot where the bending limit is a combination of the bending moment and the maximum transverse shear load (see Fig. 8.8). The laminate will fail in tension, by failure of the fibres or the outside metal layer, or in delamination (shear failure). With increasing shear force, the maximum applicable bending moment decreases, and thereby the minimum bend radius increases. The model has been validated with test results and good agreement has been obtained.

8.5.4 Modelling of lay-up processes[10]

One of the methods to manufacture large skin panels is by lay-up techniques. The panel lay-up can be modelled and optimised when the skin panel is designed. The need for optimisation comes from the use of metal layers in the hybrid laminate. These layers have discrete edges and special design rules are applied for the interaction of the edges with other features like rivet joints, cutouts, etc. In a software design environment special design routines are developed for the optimum panel design when related to costs or weight. The number of possible combinations is reduced by these procedures.

8.6 Conclusions

In this chapter an overview is presented of the characteristics, properties and production of FML. Since the laminates are hybrid materials, the characteristics and properties are related to metal alloys and to composite materials. The same is true for manufacturing processes.

Properties and characteristics

The most important properties of FML are the damage tolerance properties: the FML are better than metal alloys in fatigue and residual strength, and better than composites in impact, formability and stress redistribution at stress concentrations. Although only a limited number of FML have been developed yet, this concept will be extended to hybrid materials containing a wide range of metal volume fractions.

Manufacturing

The manufacturing processes of FML are a mixture between the processes for metals and for composites. Cutting of FML, like composites, offer difficulties like tool wear and delaminations, but FML can be machined by conventional processes. The manufacture of the reinforced skin and structural elements is based on lay-up technologies (composites) and some forming processes (metal alloys). Both processes have restrictions: the complexity and flexibility of the lay-up processes is limited by the rigid, non-pliable metal layers, and the formability of FML by the small failure strains of the fibres and the shear strain of the adhesive (causing delaminations).

Future trends are the development of cheaper manufacturing processes, based on alternatives for the lay-up of the metal layers, and innovation of methods to exploit the formability of the laminates. Other options for cost reductions are changes in pretreatment and curing processes.

Modelling

Due the short history of FML, the modelling of its behaviour and the development of simulation tools is only at the beginning.

For the property calculations a number of reliable tools are already available. The simulations of processes or material behaviour, involving plasticity, are more complex and future developments are aimed to bring the simulations to a mature level like the models for metals and composites.

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