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ORIGINAL ARTICLE

Towards a rapid, non-contact shaping method for fibre metal laminates using a laser source

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Abstract Since their initial development, fibre metal laminates (FMLs) have slowly started to be used by industry, particularly the aerospace sector. One of the reasons for the relatively slow adoption of FMLs is due to the difficulties faced in shaping them to the desired geometry. Whilst traditional processes such as roll forming are effective in shaping monolithic materials, these processes could potentially destroy the mechanical properties of the composite layer. The approached investigated here uses thermal or laser forming (LF) to shape flat panels of thermosetting glass fibre based FMLs into 2D geometries. This initial empirical investigation covers the effectiveness of the various LF processes and the effects of various parameters have on the forming process. These include laser parameters such as power and velocity and material parameters such as FML lay-up strategy, fibre orientation and comparison with monolithic materials.

Keywords Laser forming · Fibre metal laminates · Composite material · Non-contact shaping

1 Introduction

FMLs are a hybrid composite sandwich structure comprising of multiple layers of a thin aluminium alloy less than 0.5 mm in thickness and alternating layers of composite material, as shown in Fig. 1. The first FML was aramid reinforced aluminium laminate (ARALL) developed at Delft University of Technology and uses an epoxy/aramid composite system. Initial reactions to this material were positive and some in service parts, such as C-17 cargo doors, where produced [1]. However, a number of reasons prevented universal uptake including a cost ten times that of aluminium, expensive post processing, poor blunt notch strength and thickness steps that were susceptible to premature fatigue cracks. ARALLs were quickly followed by glass reinforced (GLARE) which replaced the aramid with glass fibres embedded in epoxy resin. GLARE is available in standardised forms with the number and order of layers dependent on the final application. The main advantage of FMLs over monolithic materials is greatly improved fatigue, impact and damage tolerance characteristics at a much lower average density. Mechanically similar FML structures are approximately 20% lighter than their monolithic aluminium counterparts [2, 3]. FMLs also exhibit increased corrosion resistance due to both the fibre layers inhibiting through-the-thickness corrosion and the improved corrosion characteristics of the thin alloy sheet. The fibre layers improve the panels' fire resistance as they act as a barrier preventing the outer layers of aluminium melting [1].

The shaping (or forming) of metallic structures by the application of heat is a process long used in engineering, particularly in 'heavy' engineering such as shipbuilding and building construction. Traditionally, an oxy-acetylene torch would be used by an operative of many years experience to slowly bend the work-piece to the desired shape. However, due to the nature of the process, it is difficult to predict the finished shape and requires many man hours of processing [4]. LF uses the basic techniques established in thermal bending and adds the advantage of a predictable, controllable and repeatable process. The level of control offered by LF over the thermal input makes the laser variation of thermal bending a much more of an applicable process in

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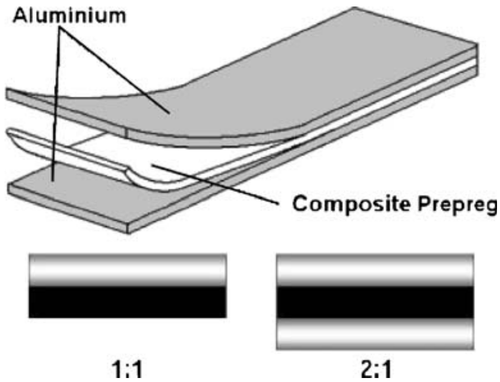

Fig. 1 Typical FML lay-ups

modern engineering. With this level of control, it is possible to apply LF techniques to material processing on the micro- and nano-scales, as well as the macro-scales. The LF process produces a bend in the material by the introduction of thermal stresses. This is achieved by passing a laser beam over the surface, which is de-focused to prevent melting occurring. This introduces internal stresses that cause plastic strains which either bend or shorten the work-piece depending on the mechanism active or can result in local elastic plastic buckling of the work-piece [5]. The active mechanism in the LF process depends largely on the thermal gradient produced through the thickness of the material. When a steep thermal gradient is induced the mechanism used is the temperature gradient mechanism (TGM) which produces bends towards the thermal source. TGM relies on compression of the unheated area by the expanding heated area to produce plastic deformation. The process utilises a localised heating of the material below its melting temperature; thus, good mechanical properties can be retained [6, 7]. When a shallow or no thermal gradient is produced, i.e. there is a constant temperature rise through the thickness, the buckling mechanism (BM) occurs. The heating causes a bulge to appear, towards or away from the source depending on internal stresses or mechanical pressures, which deforms plastically in its hotter central region but deforms elastically on its edges. On cooling the plastic, deformation remains. This method can produce bends of up to 10° per pass. When a similar thermal gradient is produced but geometrical restrains of the part do not allow buckling, the upsetting mechanism (UM) occurs. This causes a reduction in the overall length dimensions of the sample [8]. These mechanisms have been used to shape a number of different materials, such as mild and stainless steels [9, 10], titanium alloys [6], aluminium alloys [7, 11] and more recently a number of non-metallic materials including silicon [12] and plastics [13]. LF has also been shown to produce parts with acceptable material properties [14] and surface finish [15]. This is achieved by control of the energy density incident to the part.

The initial work in the forming of FMLs was undertaken by Edwardson et al. [16] who investigated a variety of FML lay-ups and materials using a 1-kW CO_2 source to shape them. Edwardson identified the TGM as an applicable method of shaping FML panels and identified a number of variables of importance to the process of laser forming of fibre metal laminates. These include the quantity of layers present in the laminate as well as the direction of fibre orientation relative to the laser traverse line as well as some modes of failure which occurred during the processing. The purpose of the work presented here is to further this initial work and to add further detail with particular attention to the effect of composite layer variables on the laser forming process. The flexible nature of LF indicates a possible application in the aerospace industry. The low production levels (when compared with automotive and consumer products), high value parts and near constant design changes suit the flexibility and economic demands of laser processing [17].

2 Experimental procedure

2.1 Hardware

A GSI LumonicsTM Lightwriter SPe 35 W Nd:YAG laser system, operating in continuous wave mode at a wavelength of 1.064 μm, was used for the forming process. The beam was rastered across the work-piece by a pair of fast scanning galvanometer driven mirrors through a flat field optic with a field area of 150×150 mm and a spot diameter of 0.2 mm. The work-piece was clamped on a stand to which was also attached a simple laser triangulation system (Fig. 2a). This system was used to record the change in height of the bending arm of the work-piece after each laser scan. The semi-automated system was run on a visual basic programme and was required to be activated by the user when to take a reading. The height value was recorded 25 s after the scan to ensure that the forming process was complete. Simple trigonometry was used to convert the voltage output to a bend angle. The FML coupons were cut using a guillotine to 40×40 mm, with the form line in the middle of the coupon in line with the rolling direction of the aluminium. The upper surface was cleaned with acetone and ethanol prior to being coated with graphite to increase the absorption of the 1.064 μm radiation. The graphite was removed and reapplied after ten scans of the laser beam to limit the reduction in bend rate caused by the graphite burning off. The dwell time between passes was set at 30 s to reduce the latent heat build-up and allow the steepest possible temperature gradient. The coupons were clamped 4 mm from the irradiation line with a 16-mm wide aluminium clamp (Fig. 2b). Empirical work was conducted

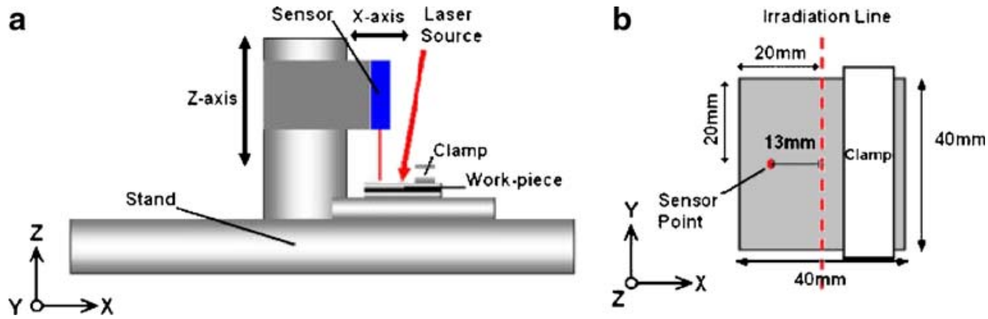

Fig. 2 **a** Clamping arrangement and **b** work-piece schematic

to determine the effects of dwell time between scans, graphite reapplication rate and repeatability of the tests. The repeatability tests were carried out over a number of months at different times at a high energy density to amplify any errors. The results were within 5% of each other indicating good repeatability. Thermal analysis of the LF process used K type thermocouples with a temperature range of −200°C to 1,370°C. The data were recorded using an Agilent 34970A data acquisition unit, collecting data at up to 250 times a second.

2.2 Material

The FML used in this study consists of layers of 240×200×0.3 mm aluminium 2024-T3 bonded to a 0.125-mm layer of unidirectional E-glass fibre contained in a FM94 matrix. The mass of the fibre is 300 g/m^2, and the composite was cured in a hot-press. The aluminium was cleaned using both acetone and ethanol before the pre-preg was applied with the fibre direction in parallel to the rolling direction of the aluminium. The lay-up was then placed in a PTFE film-coated mould and cured at 120°C for 1 h. To ensure a consistent manufacturing process, a portion of each plate underwent a peel test to calculate the Mode I facture toughness (G_{Ic}) of the sample. The plate contained a 50×50-mm aluminium foil sheet which formed a pre-crack for a subsequent peel test to measure the Mode I fracture toughness of the aluminium–composite interface. Using Berry's method, a value for G_{Ic} was calculated as 69±5 J/m^2, which showed good consistency in the inter-laminar strength of the material; therefore, a constant product was being produced [18].

3 Results and discussion

The variables encountered when investigating laser forming of FMLs falls into two main areas: process and material parameters. The first area investigated was the effect of processing parameters, which can be separated into two sub-sections. The first area of investigation is to ascertain which of the three recognised mechanisms (BM, TGM, UM) would work with FMLs (Section 3.1.1) and the next stage being what effects the various laser parameters have on the forming process (Section 3.1.2). The next area to investigate is the material parameters which influence the formability of FMLs. These can be separated into two main areas, stacking sequence (Section 3.2.1) and composite layer (Section 3.2.2). The stacking sequence refers to the number and order of aluminium and composite layers, whereas the composite layer refers to the parameters of the composite, such as fibre angle relative to the forming line and the composite layer thickness.

3.1 Processing parameters

3.1.1 Forming mechanism

As briefly described in the introduction, there are three main recognised mechanisms for LF. Of these, the UM can be discounted since it results in a change in dimensions rather than bending the material. Of the remaining mechanisms, TGM has an advantage over BM, due to the lower levels of thermal input introduced into the sample. TGM was tested initially and gave positive bends towards the beam when employing a spot size approximately the same diameter as the thickness of aluminium (0.2 mm spot diameter with 0.3 mm aluminium thickness). With the low power system (35 W max output 10 mm s^{-1}), bends of approximately 0.2° to 2° per pass, depending on the lay-up (3–2 to 1–1), were achieved with little apparent damage to the FML.

To achieve the BM, a spot size of approximately 4 mm was used (35 W 10 mm s^{-1}). BM bends were produced which propagated away from the source as a result of the strains imposed on the upper aluminium surface by the neighbouring composite layers. However, due to the nature of the BM mechanism, where a shallow thermal gradient is required through the thickness of the material, temperatures exceeding the maximum working temperature of the composites were required to produce a bend in the aluminium layer. These excessive temperatures led to a delamination of the composite layer either in the form of a buckle with low scan strategies (Fig. 3a) or complete delamination of the layer at higher scan strategies (Fig. 3b).

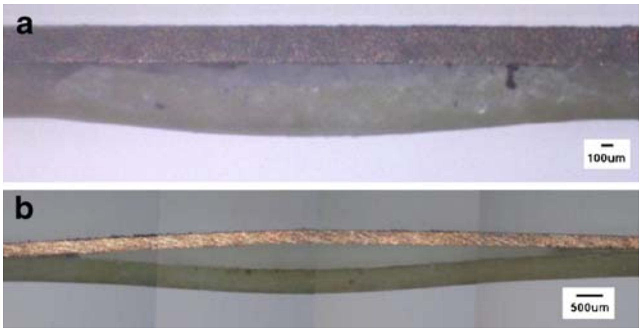

Fig. 3 **a** Delamination following BM forming of FMLs after two passes **b** after ten passes (composite image)

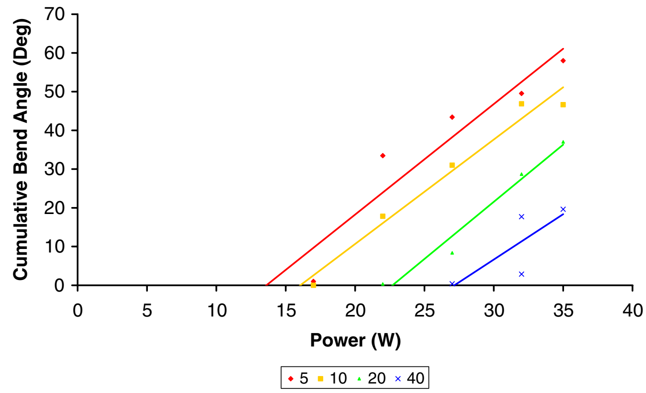

Fig. 5 CBA results after 30 passes at varying powers for various velocities on a 1:1 0°FML

Delamination of the composite layer was observed in samples which had yet to exhibit a bend (Fig. 3a). As the failure of the material structure was observed at an energy input below the threshold to produce a bend, the BM was discounted as a forming mechanism for FMLS. These findings were by Edwardson et al. [16] who reported the unsuitability of the BM for producing bends in FML panels.

3.1.2 Laser parameters

The first parameter investigated was the effects of varying number of irradiations. A 2:1 0° (two aluminium–one composite layer with the fibre orientation 0° from the scan line) sample was formed at 32 W and 10 mm s^{-1} with the parameters described in section 2 and was irradiated until there was no further increase in cumulative bend angle (CBA), in this case after 160 passes. The sample was measured after each pass, and the data are presented in Fig. 4. The characteristic shape of a monolithic LF sample is present with the high rates of bend (approximately 0.5°) per pass initially (<10 scans) which then tales off (<0.2° per pass) for reasons such as strain hardening, section thickening, absorption variation, thermal effect and geometrical effects [19] giving the curved CBA results characteristic of LF.

The effect of varying laser power and velocity had on the forming rates of the FMLs is shown in Figs. 5 and 6. As power is increased and velocity decreased, the CBA achieved increases as the incident energy increases. However, with high power levels and low velocities, which give the greatest BRPP, undesired heating of the composite occurs, and its effects are discussed in section 3.3. Where the power levels increased beyond 35 W with slower velocities, a BM mechanism occurs due to the build-up of heat within the material bulk, reducing the temperature gradient. This heat build-up can be controlled by altering the dwell time between passes or by a method of forced cooling, which itself has associated problems (Section 3.3).

3.2 Material parameters

3.2.1 Stacking sequence

The most obvious parameter influencing the formability of FMLs is the quantity and order of the layers of aluminium

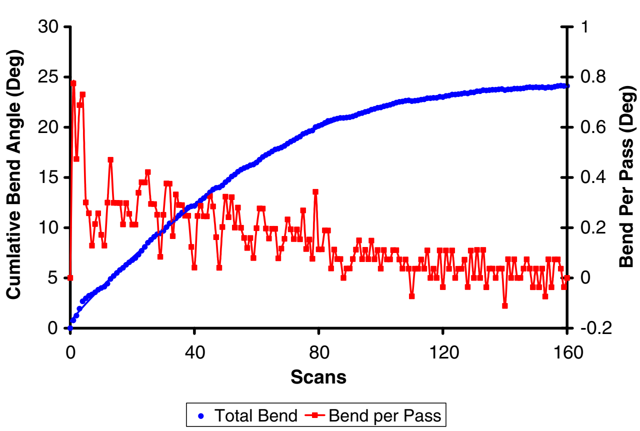

Fig. 4 Effect of multi-pass forming strategy on CBA and BRPP

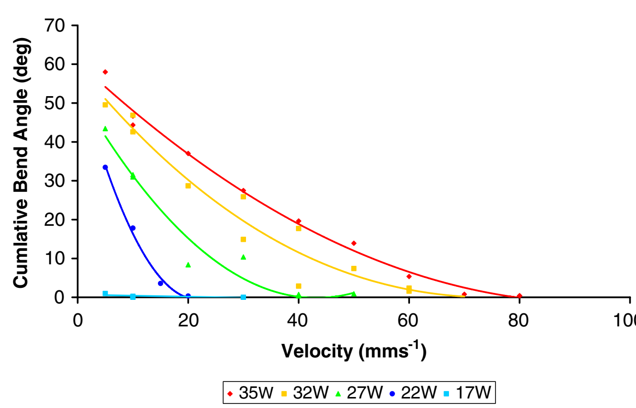

Fig. 6 CBA results after 30 passes at varying velocities and powers for a 1:1 0°FML

and composite. As the TGM only occurs with metallic materials, the upper aluminium layer must act as a bending arm to ‘pull’ the remaining layers of the FML to shape. This has some obvious limitations, such as the total achievable bend angle, as this is limited by the bending force that can be attained in the aluminium layer. As commercially available FMLs have a maximum thickness of aluminium of 0.5 mm [2], this limits the number of layers formable by this method. In this study, with a 0.3-mm aluminium layer, the maximum FML thickness formable was a 3:2 lay-up (Fig. 7).

The addition of a single composite layer (1:1), with the fibres oriented in the laser scan direction, reduced the CBA after 30 passes from 68° to 45°, a drop of 33% from a single aluminium layer (1:0). This trend continues with 2:1 lay-up reaching a CBA of 30° (a drop of 33% from a 1:1 lay-up), 2:2 reaching 14° (a 52% drop from 2:1) and 3:2 reaching 4° (a drop of 73% from the previous lay-up). This is consistent with a reduction in the ratio of the formable depth to the material thickness, which supports earlier findings that the bend is formed due to the moment induced in the upper surface [16]. The addition of layers to the FML has an advantageous effect in that the response of the material to LF is near-linear as opposed to the non-linear response of aluminium (Fig. 8). The reasons for the non-linear response, as discussed by Edwardson et al. [19], are thought to be a combination of factors such as absorption coating burn-off, work hardening and geometrical effects. These results show that the lay-up strategy of FMLs affects their formability greater than any other variable. This near-linear response should allow for easier closed-loop control compared to monolithic materials and an increase in the predictability of the resulting shape.

The effect of FML lay-up on the real time bend rate is just as significant and is shown in Fig. 9. LF of traditional monolithic materials produces no springback [5], where the maximum bend angle reached is the final bend angle, whereas LF of FMLs suffers from springback. In the case of a 1:1 lay-up, up to 27% of the maximum bend angle reached is lost before the sample settles to its final angle. Springback occurs in traditional forming due to the large amounts of elastic strain energy which is caused by the highly non-linear deformation process. This elastic energy is contained whilst the sample is in dynamic contact with the die, but on removal of the die, this energy is released causing the sample to deform, generally towards its original geometry. LF of monolithic materials does not exhibit this feature as the whole work-piece is subject to the forming process, in LF of FMLs only the top layer is thermally formed. The neighbouring layers are mechanically shaped by the thermally formed layer pulling them mechanically, and as with any mechanical shaping, elastic recovery will occur. This elastic recovery is more pronounced in the lay-ups with equal or greater ratio of composite to aluminium (1:1, 1:2, 2:2, etc.) as elastic modulus reduces increased rates of springback occur. In these lay-ups, the mechanically formed part consists of equal if not greater volume of composite material, which lowers the modulus of elasticity of the sample as a whole, thus making it more susceptible

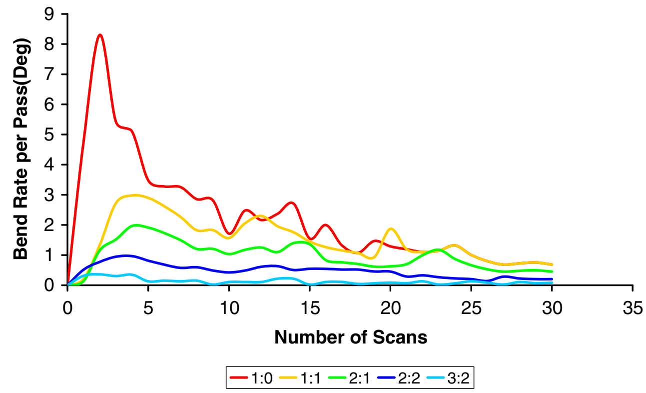

Fig. 8 Number of scans versus bend rate per pass, for FMLs with different lay-ups (1:0, 1:1, 2:1, 2:2, 3:2) processed at 35 W, 10 mm s^{-1}

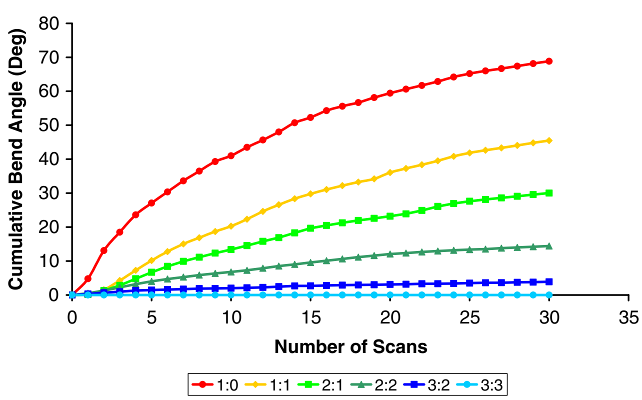

Fig. 7 Number of scans versus cumulative bend angle for FMLs with different lay-ups (1:0, 1:1, 2:1, 2:2, 3:2) processed at 35 W, 10 mm s^{-1}

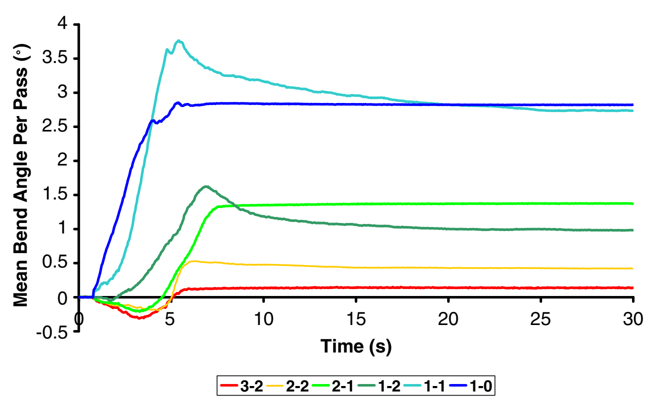

Fig. 9 Real time bend angle propagation on various FML lay-ups, processed at 35 W 10 mm s^{-1} for a single pass

to the springback phenomena. The elastic counter bend effect during the initial heating stage is also amplified by the addition of further composite and aluminium layers. With a single layer of AL2024-T3, no counter bend (negative bend due to thermal expansion during the initial stages of heating) was detected but more complicated lay-ups showed an increase in the counter bend angle up to nearly 230% of the final bend angle achieved, in the case of a 3–2 lay-up. This is due to the stresses present in the laminate system from the curing stage where the differing thermal expansion coefficients of the aluminium and composite cause stresses on cooling, or the method of LF used for FMLs, where the top layer of the work-piece undergoes the forming process and it 'pulls' the lower layers towards the laser source to form the bend. These induced stresses load the work-piece during the elastic phase of the LF process causing the counter bend.

3.2.2 Fibre layer parameters

Due to the anisotropic nature of composite materials, it was necessary to investigate the effect various composite properties have on the formability of FMLs. These can be broken down into the following areas: fibre orientation, layer thickness, fibre properties and matrix properties. Of these, fibre orientation and layer thickness were the two main parameters investigated.

Fibre orientation A number of samples were produced to investigate the effect of fibre orientation. Each of these was a 1:1 lay-up of aluminium 2024-T3 and unidirectional E-glass epoxy pre-preg with a fibre volume of 56%. The fibres were at various orientations (0°, 15°, 30°, 45°, 60°, 75° and 90°) from the bend line. These samples were processed altering the laser power and traverse velocity, and the resulting bend angles were recorded using the method previously described. The initial findings showed that as the fibre was oriented away from the bend line, the total bend angle achieved was reduced; this is illustrated in Fig. 10. This graph shows a clear reduction in the CBA as the fibre orientation angle (FOA) increases. These effects can be separated into two main areas, low pass scan strategies (<5 scans) and high pass scan strategies (≥5 scans). The effect FOA has on the CBA at low scan strategies appears to be variable in nature which suggests at small bend angles, it is other parameters, such as residual stress, that have a greater effect on the bend. With high scan strategies (higher total bend angles), a more uniform effect is observed. In these cases, a drop in bend rate is not observed until a fibre orientation angle greater than 15° is reached. The bend rate then drops off until an angle of 60° is reached, then the reduction plateaus off and remains roughly constant up to an angle of 90°.

If the results from Fig. 9 are normalised against the CBA for a FOA of 0° (shown in Fig. 11), the effect of fibre orientation on the CBA is seen to be more predominant. All

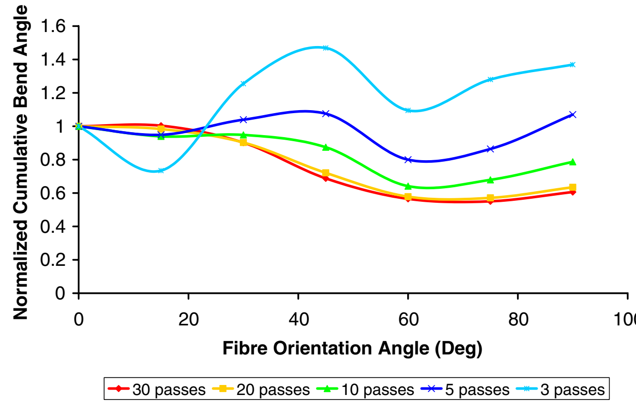

Fig. 11 CBA of 1:1 lay-up for various fibre angles normalised against 0° result

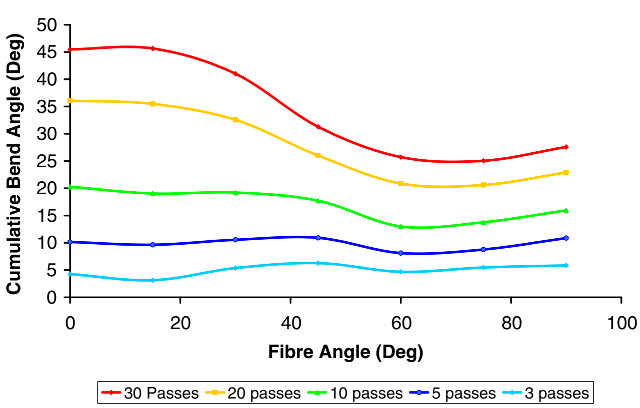

Fig. 10 Cumulative bend angle verses fibre orientation angle verses fibre orientation angle for various FML lay-ups. Samples processed at 35 W, 10 mm s^{-1}

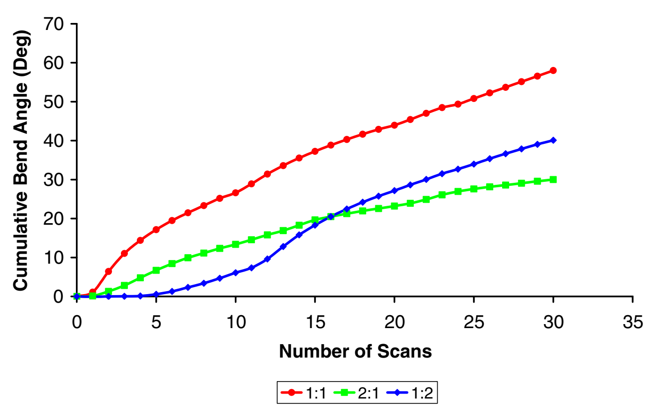

Fig. 12 Number of scans verses cumulative bend angle for 1:1, 2:1 and 1:2 lay-ups. Samples processed at 35 W, 10 mm s^{-1}, 0.2 mm spot size and 30 s dwell

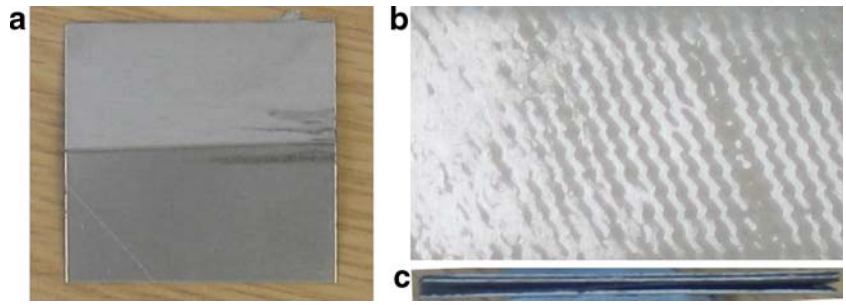

Fig. 13 **a** Delamination due to overheating, note clean surface, **b** delamination due to peel note rough finish and **c** delamination of lower layers of sample due to forced cooling

scan strategies show this 'wave' effect, starting with higher CBAs, and as the FOA moves further from the normal the CBA reduces, however, the effect becomes more uniform at higher pass rates (10+ passes). This is due to the effect that off-axis fibre angles have on the stiffness of composite materials [20].

Composite layer In commercially available FMLs, the composite layer will be a combination of unidirectional fibres with varying orientations, creating a composite layer often thicker than the aluminium. The effect this has on CBA is shown in Fig. 12 and is similar to the results previously discussed with the increase in thickness between 1:0, 1:2 and 2:1 (0.3, 0.55 and 0.725 mm, respectively) causing a reduction in the CBA. However, an increase in the composite thickness reduced the initial rate of bend in the first 11 passes. After this, the more characteristic LF curve is seen; a similar effect is noted by Dearden et al. [21]. Here, mechanically pre-bent samples with a negative-form angle were treated by LF to remove this distortion. This suggests that due to the different contraction rates of the composite and aluminium, the sample was pre-stressed even though this was not visually apparent. This, therefore, will affect the formability of any asymmetrical FMLs where the composite is of greater thickness ratio than the aluminium.

3.3 Failure modes

During processing, a number of different failures observed can be separated in to two main areas, structural failures which is characterised by the failure of the integrity of the structure of the material (Section 3.3.1) and material failures where the process parameters have altered the properties of the material (Section 3.3.2).

3.3.1 Structural failures

Structural failures were limited to delamination of the sandwich structure but were caused by a number of different factors. The first delaminations occurred exclusively between the surface aluminium layer and the initial composite layer. This was characterised by a visual change in the composite and, on inspection, a smooth break between the composite and aluminium (Fig. 13a). Mechanical failures were characterised by a rough texture on the aluminium surface, as witnessed during peel testing (Fig. 13b). However, the smooth texture witnessed with this failure indicates that overheating occurred, causing the matrix to separate from the aluminium during the LF process. In order to prevent this, a number of different forced cooling techniques were attempted which led to delamination between the lower layers (Fig. 13c). This was

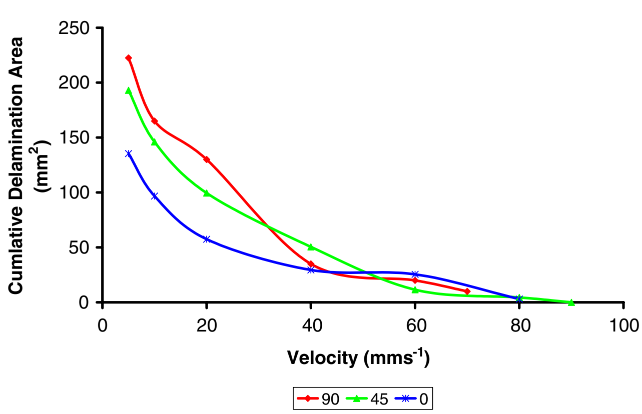

Fig. 14 Cumulative delamination area verses velocity for various fibre orientations for the clamped and unclamped side of the sample

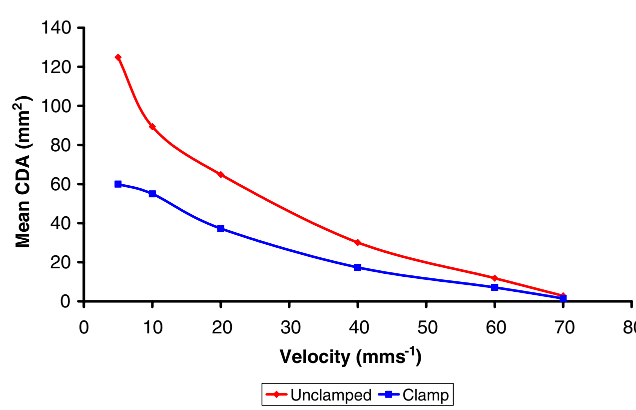

Fig. 15 Mean cumulative delamination area verses velocity for the clamped and unclamped side of the sample

due to the variable rate of cooling between the layers, which led the lower layers to contract at a greater rate than the upper layers causing delamination. These tended to be complete failures with the lower surface completely delaminating.

The final form of structural failure witnessed was due to fibre orientation and occurred when the fibres were orientated further away from the line of irradiation (Fig. 14). Here, delamination occurred due to a combination of factors. The excessive heat input at lower velocities caused some softening of the matrix, which, when combined with the bend angle of the aluminium exceeding the minimum radius achievable by the E-glass rovings, caused the laminate structure to break down. This is supported by the smooth surface finish under the delamination showing that a non-mechanical failure of the bond between aluminium and composite had occurred. Also, as the orientation of the fibres increased away from the irradiation line, the CDA increased and the variation in mean CDA, with the clamped side of the work-piece suffering less CDA than the un-clamped (Fig. 15).

3.3.2 Material failure modes

The possible effect of LF on aluminium has been well documented [8], and the same effects are in evidence here with the presence of sub-grain structures, partial melting around grain boundaries and melting and re-solidification of the upper layer. This can be controlled by limiting the energy density the aluminium is exposed to. Another well-documented effect of LF is thickening of the work-piece. This was witnessed to a greater degree in the FML sample when compared to the single thickness of aluminium and is currently under investigation.

The composite layer is affected in two ways, thermally, due to laser parameters exceeding the maximum working temperature of the composite and mechanically, due to the bend angle causing failures of the fibre/resin system. Of the thermal effects, the main problem was burning of the matrix (Fig. 16a). Mechanical effects to the composite were cracking in the matrix (Fig. 16b) and the fibres (Fig. 16c), due to the bend angle exceeding the minimum curve achievable by the composite.

4 Conclusions

In this study, the effects of LF mechanism, laser parameters and material parameters have on the LF of FMLs, the following conclusions can be drawn.

1. Of the three main thermal laser-forming techniques, TGM is the only mechanism which gives an out-of-plane bend without considerable damage to the laminate. The parameters required for use of a BM causes delamination of the structure and heat damage to the composite layer. The UM is unable to be produced in FMLs due to the through heating of the structure required.
2. The TGM is used to produce a bend in the layer of aluminium adjacent to the laser source. This then mechanically forms the lower layers in to a bend.
3. Variation in the laser parameters of power and velocity has the same effect as with monolithic materials as they do with FMLs. An increase in incident energy, either by an increase in power or decrease in velocity, leads to an increase in both bend rate per pass and cumulative bend angle. However, an increase in incident energy causes damage to the structure and properties of the FML.

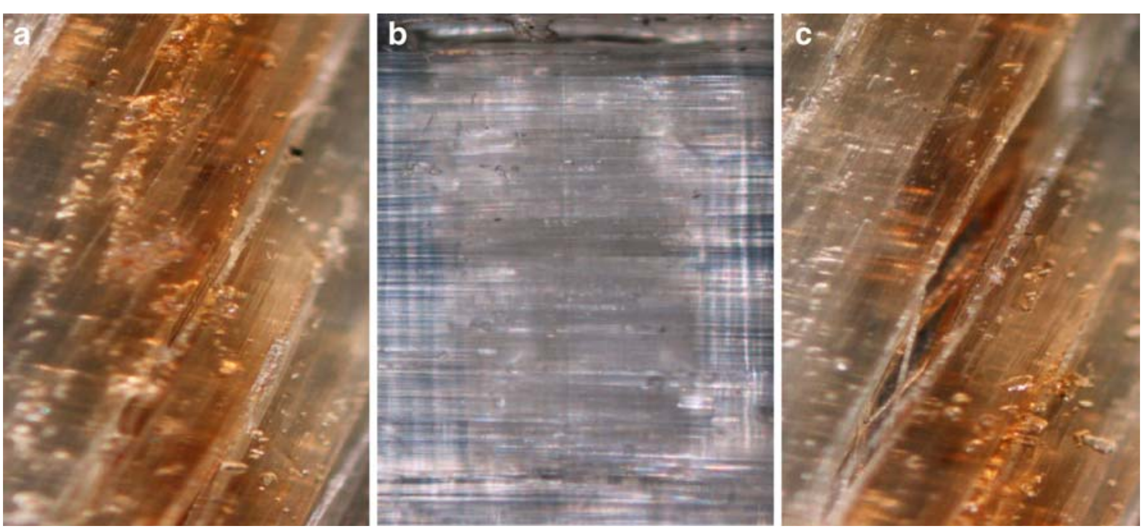

Fig. 16 Image of **a** burnt area of composite, **b** cracking through thickness of fibre and **c** crack in matrix at ×5 magnification

4. The effect of stacking sequence on LF is to reduce the CBA achievable for a given incident energy. The laminate nature of FMLs means that only the upper surface can be used to create TGM. Therefore, as the number of layers increases, the CBA reduces as only a finite amount of force is available to pull the lower layers to form the bend.
5. An increase in lay-up also causes the BRPP to vary less showing that lay-up has a greater effect on the forming rate than other factors discussed by Edwardson et al. [17].
6. The stacking sequence also has an effect on the real-time propagation of the bend. Springback occurs in LF of FMLs due to the lower modulus of elasticity of lay-ups with a greater proportion of glass fibre than aluminium. The counter bend witnessed during the initial heating stage of TGM is also amplified by increasing the stacking sequence. This is due to the stresses imparted on the system by the composite layers.
7. Fibre orientation angle has a detrimental effect on the CBA. As the fibres are rotated away from the laser traverse direction, a reduction in CBA is observed. This reduction takes place once the FOA has exceeded 15° and plateaus out at 60° to a constant level.
8. Addition of extra composite layers (1:2) causes stresses in the work-piece which must be overcome in order to produce a bend.
9. A number of failure modes such as delamination due to thermal input forced cooling and fibre orientation and material failures such as burning and matrix and fibre cracking have been identified and characterised.

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