An experimental and numerical study on the thermal V-bending mechanism of fibre metal laminates

Q. Lin[1a], Z. Guan[1] and W. J. R. Christian[1]

[1]School of Engineering, University of Liverpool, UK

[a]qiushi.lin@liverpool.ac.uk

Abstract

A technique is demonstrated for obtaining data suitable for validating finite element models of the forming behaviours of fibre metal laminates (FMLs) during V-bending at elevated temperatures. Experimental methods including digital image correlation (DIC), ultrasonic C-scan and microscopy were applied to analyse the reshaping mechanism during the forming process, and characterise defects after the process. Finite element models for the specimens were compared with the experimental results, demonstrating that the final shape of the specimens and the potential defects can be predicted.

Introduction

Fibre Metal Laminates (FMLs), which are hybrid composites of metallic sheets and fiber-reinforced polymer bonded together, have had a great impact across many industries due to their high specific strength and stiffness, high fatigue resistance and damage tolerance. However conventional manufacturing approaches for FMLs have high costs. Forming the pre-bonded flat FML sheets directly within a single step into the required shape has the potential to help reduce the manufacture costs [1]. To accurately predict the shape of manufactured products and to minimise the potential defects caused by the forming process, finite element simulation has been used to predict the pressed shape of FML specimens [2]. A drawback of the current finite element analysis lies in the difficulty to validate the finite element model with experimental results because it is difficult to record the strain evolution during the thermal forming process through the thickness of the FMLs.

The purpose of this study is to obtain good predictions with finite element models of the behaviour of FMLs during thermal V-bending, so that the forming parameters for further products can be optimised based on the modelling. Therefore, experimental methods including DIC analysis, ultrasonic C-scan and microscopy were applied to provide data for the validation of the finite element models. Based on the measurements, the experimental results of primary deformation data such as the final shape of layers, the flow of polymer matrix, and the inter-ply slippage between layers were compared to the results from numerical modelling.

Experimental Method

The FML flat plates were manufactured by pressing 2 pieces of 1.6mm-thickness 2024-O aluminium plates, 2 pieces of 0.7mm-thickness woven glass fibre reinforced polyamide 6 (PA6) inner layers, and 2 pieces of 0.6mm-thickness bonding-support PA6 films together with a hot press at a temperature of 225°C, which is higher than the melting point of PA6. The FML flat plates were then cut into 120mm by 25mm flat specimens with an average thickness of 5.35mm. One edge of each specimen was painted with a fine speckle pattern to enable DIC measurements during the pressing process. To bend the specimens into a V-shape, a pair of moulds with the bending angle of 90° and punch radius of 4mm were fixed onto a 200-ton hydraulic press. Four cylindrical thermo-statically controlled heaters were mounted inside four pre-drilled holes in the moulds to heat the specimen to the target temperatures of between 170-190°C. Four thermocouples were fixed onto the moulds and specimen to monitor the forming temperature.

During the forming process, the specimen was put on the mould and pre-heated to the target temperature by the heaters in the moulds. The specimen was then formed by the mould into a V-shape at a pressing speed of 2mm/s. The forming process was recorded using a stereoscopic DIC system (Q-400, Dantec Dynamics, Germany) equipped with 50mm lenses, and also a thermal imaging camera (thermoIMAGER, Micro-epsilon, Germany) so that the strain on the edge area of the specimen and the temperature field on the surface of the mould were measured. The temperature of the specimen was kept constant for 1min after the finish of pressing process, then the heaters were turned off and the specimen allowed to naturally cool with the press closed.

After the the forming process, multiple experimental methods were applied to test the forming quality of the specimens. Ultrasonic C-scans were used to acquire images of potential delaminations on the bonding surface between the surface aluminum layer and composite interlayer within the flat portions of the specimens. The same stereoscopic DIC system as used for the strain measurement during the forming process was also used to measure the geometric shape of the radius of the bended specimens.

Optical microscopy was used to identify defects within the composite layer on the edge of specimens at the radius area. The experimental results of strain evolution, geometric shape and defects found in the specimens were compared with data acquired from the finite element simulations of a similar thermal V-bending process based on Abaqus.

Results and Discussion

As shown in Fig.1 (A), the shear strain field acquired from DIC analysis and the amplitude acquired from ultrasonic C-scan were put into a same coordinate system for comparison. The shear strain was concentrated on the bonding area between PA6 and aluminium layer from 0 to 8mm on X-direction, and the magnitude of the shear strain on the inner bonding surface is higher than it on the outer bonding surface. The ultrasonic C-scan result on the outer bonding surface showed an enhanced reflection from a delamination extending from the radius to around 10mm in X-direction. This indicated that a delamination had formed in the area. However, there was no such delamination detected on the inner bonding surface.

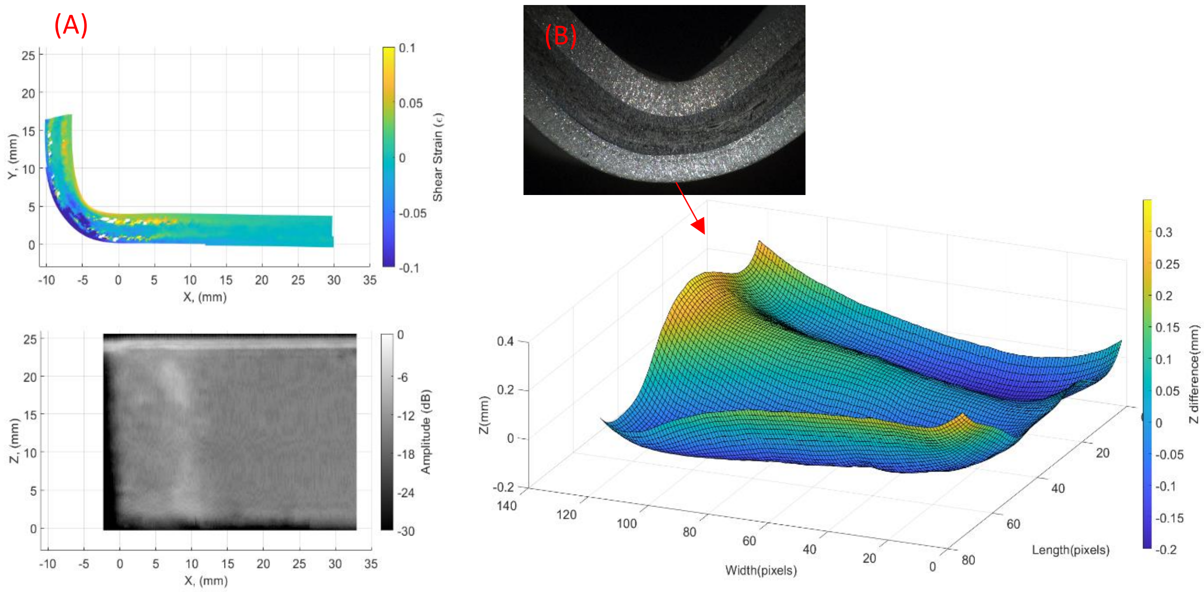

Figure 1, (A) the DIC result of shear strain evolution compared with the ultrasonic C-scan result on the bonding surface, (B) The difference of the shape of radius tip surface of the specimen compared to a curve fitted standard cylinder.

The geometric shape of the radius tip surface was compared to a fitted cylinder to get a difference map, which is shown in Fig 2 (B). The test result showed that the specimen manufactured with higher pressing depth results in smaller tip radius which is also closer to the target radius of a perfect cylinder. The primary irregular shape caused by the V-bending process was located on the tip edge area of the specimen. Overall, the FE simulation results showed a similar strain evolution as the DIC result, while more study is still needed on the simulation of defects and shape accuracy.

Conclusion

This work demonstrates a technique for obtaining data suitable for validating finite element models to predict the forming behaviours of FMLs after V-bending at elevated temperature. Current results show that the experimental methods are able to quantitatively analyse the forming quality of the FML specimens and validate the FE modelling.

Reference

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