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ITERATIVE LASER STRAIGHTENING OF WELD-DISTORTED PLATES

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Abstract:

Laser forming of non-developable surfaces requires an accurate model of both the bending and membrane strains generated. An iterative approach to laser forming can increase the accuracy of the final shape generated without the need for extreme levels of accuracy in material characterisation and process modelling, by using closed loop control of shape generation. In this paper, we report a new approach to iterative laser forming of non-developable surfaces, based on a fixed scan lattice where the required membrane strain is calculated from a finite element simulation. This forming approach has been used to straighten friction stir-welded AA2024T3 plates. To the best of our knowledge, this work represents the first iterative laser correction of distorted structures.

Keywords: laser forming (straightening), surface treatment, iterative procedure, finite element simulation, CO₂ continuous wave laser.

1. Introduction

Weight-reduction is a main issue for all vehicles, especially for aeroplanes, to decrease fuel consumption. Welding is the best way for cost-effective incorporation of lightweight monolithic materials into vehicles. However, there are currently major problems associated with welding: one of them is the unwanted distortions due to thermal stress. Post-process correction of distortions is of great interest for the aircraft manufacturing industry and laser forming is a promising process for the straightening of such distorted welded-plates. In this paper, we investigate the straightening of distorted friction stir-welded AA2024T3 plates.

The relationship between the laser parameters and the corresponding plate bending is required in order to understand and control the laser forming process. In 1994, Vollertsen [1] stated a simplified two-layer model to link the bend angle to the material properties and laser parameters. Subsequently, a more complex relationship based on the thermal field and the size of the plastic zone was established [2]. McBride *et al.* [3] developed a combined numerical-analytical model that relates the bend angle to the laser line energy (the laser power divided by the laser speed) that incorporates important forming features such as the line energy threshold below which no laser forming will occur and the decrease in forming efficiency at higher line energies. The model also shows the increase in induced membrane stress (responsible for the so-called 'shortening mechanism') as the line energy increases, and therefore describes the interaction between the bending and shortening mechanisms in a

unique way. Laser forming of non-developable surfaces requires an accurate model of both the bending and membrane strains generated.

An iterative approach to laser forming can increase the accuracy of the final shape generated without the need for extreme levels of accuracy in material characterisation and process modelling, by using closed loop control of shape generation. Iterative laser forming of non-developable mild steel specimens was reported by McBride *et al.* [4]. Firstly, a calibration of the induced bending and membrane stress against laser line energy was performed. Secondly, a lattice laser scan path was used as a practical implementation for iterative control of the forming process. Pillow and saddle shapes were formed successfully from flat plates of uniform thickness.

The iterative laser forming process described in [4] used an analytical model to calculate the bending and membrane strain required to form flat plates of uniform thickness into the required shapes between each forming iteration. Ultimately, we would like to form plates of varying thickness, in which the strain distribution would be extremely difficult to describe with an analytical model. In order to extend this work for plates of varying thickness, we have extended the iterative laser forming technique to incorporate calculation of the required strain field by a finite element method. Other authors have used a finite element model to compute the required membrane strain to form pillow and saddle shapes from curved plates in single pass forming [5, 6]. In this paper, the finite element method is incorporated into the iterative laser forming.

Firstly, a brief summary of the previous iterative laser forming process is presented. Secondly, the calculation of the membrane strain by the finite element method is described, along with its incorporation into the iterative laser forming process. Finally, the modified iterative laser forming approach is applied to the straightening of friction stir-welded AA2024T3 plates.

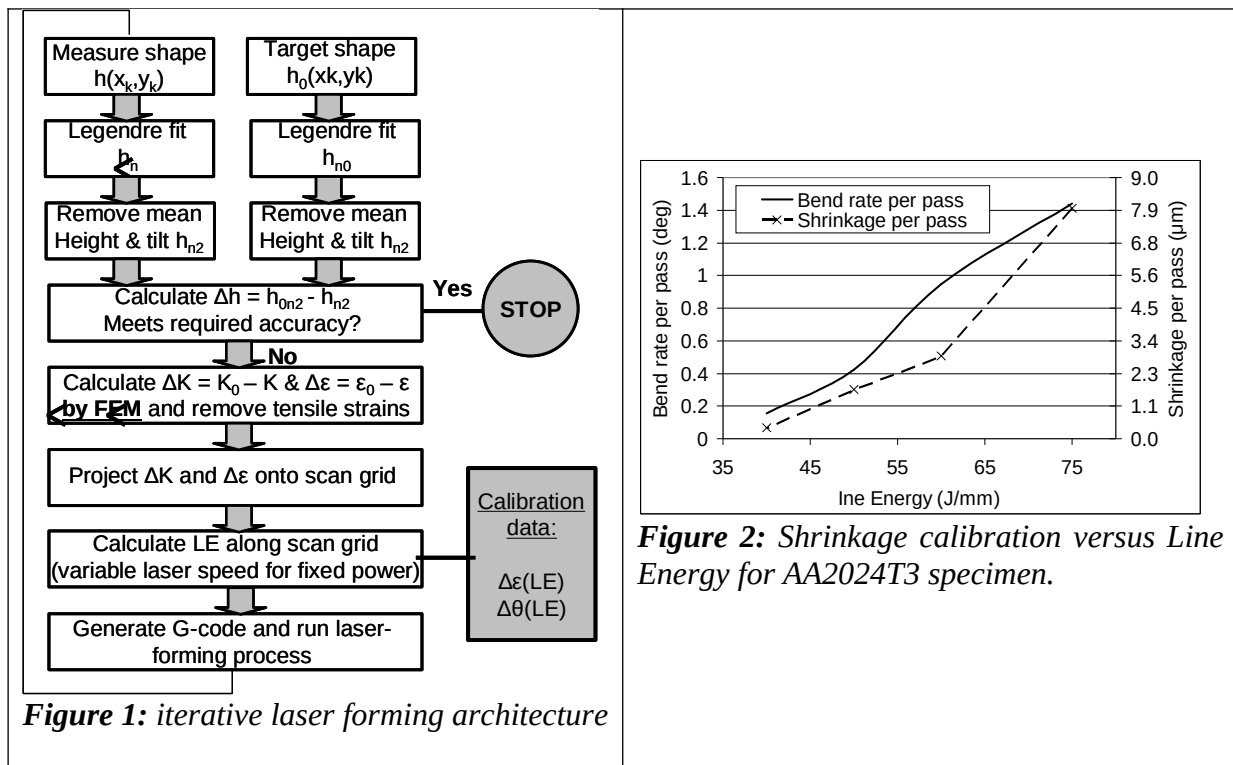
2. Iterative Laser Forming Process (ILF)

The iterative laser forming has been developed by McBride *et al* [3, 4]. It has been used firstly to form pillow and saddle shapes from mild steel specimens. Then it has been employed by Bardin to straighten welded aluminium alloy specimens (results not yet published).

The iterative laser forming (ILF) procedure as described in [4] is depicted in **fig. 1**. The edges of the plate are aligned with x- and y-axis at the beginning of the process (and the plate is fixed in its centre with a bolt tightened at 3 N.m with torque wrench). The target shape of the flat shape is then chosen. The ILF consists of sequentially calculating the difference (shape residual) between the measured shape of the specimen and the target shape, where both shapes are described by a set of 8th order Legendre polynomials. ILF stops when the shape residual meets the required shape accuracy.

At each iteration, the bending and membrane strain distributions required to induce the shape residual are calculated from an analytical model. (It is at this stage that the finite element model, described in the next section, is introduced in place of the analytical solution). The strain field must be compressive because the laser forming process generates a

compressive strain field. Therefore a mathematical correction must be applied to the computed strain field in order to obtain a strain field that is compressive everywhere. In general, we apply a radially-varying compressive strain to modify to the strain field. Once the required curvature and strain field distributions are known, they are projected on the lattice laser scan path [4].



Then bending and membrane strain are converted to a corresponding line energy using a calibration database which originates from basic experiments [3, 4]. Calibration experiments were performed in a similar way for the AA2024T3 material used in the experiments reported in this paper: the calibration curves are shown in **fig. 2**. The laser power is kept constant and so the laser scan speed varies continuously along each line that comprises the lattice pattern of the scan path during each iteration. Currently the ‘bending’ scan is applied first on the top surface of the plate, after which the plate is turned over and the ‘membrane’ scan is applied on the bottom of the plate, which provides an accurate and stable solution [4].

3. Finite Element Modelling for the ILF

In the modified iterative forming approach, bending strain is calculated from the curvature of the shape residual as in the original method, whilst the membrane strain is

calculated with a finite element model. The iterative laser forming program has been written in Matlab, so we chose the Comsol finite element package for its compatibility with Matlab.

The use of a complete thermo-mechanical simulation would take too long to run between forming iterations. Therefore, some simplifying assumptions are made for the finite element simulation:

- ✓ The mechanical problem is purely elastic and the problem is static
- ✓ The initial plate after each iteration is free from residual stress
- ✓ Large deformations are permitted
- ✓ The input condition is the vertical displacements (shape residual)

In our current model, the strain field generated on the mid-plane of the plate due to applying the shape residual to an initially flat, stress-free plane plate are computed. The 370 mm x 250 mm x 3 mm are modelled by a mesh comprising 2458 Lagrangian elements with 4th integration order and 15246 degrees of freedom. The software was validated for large deformation by comparing the results of thin plate theory for a saddle and pillow simulations. The simulation of these problems takes less than 15s on AMD bi-processor (2GHz) computer with 2 GO memory. The membrane strain distribution was converted to be compressive everywhere as described above in the original iterative forming procedure.

4. Experimental straightening of stir-welded plates

The laser used for the experiments was a TRUMPF TLF 2700 Turbo, a 2.7kW CO₂ laser with standard metal-cutting laser optics and nozzle. The beam was used beyond focus to provide appropriate spot size for laser forming. The setting parameters for the laser straightening of stir-welded AA2024T3 plates were: laser power fixed to 1000W and beam diameter of 9 mm. The laser scan speed varied along the lattice scan to provide line energies in the range 35 J/mm to 75 J/mm, as calculated from the shape residual. The friction stir-welded AA2024T3 specimens measured 370 mm x 250 mm x 3 mm and were supplied by BAE SYSTEMS. The plates were coated with graphite to enhance the absorption of the heat flux. The shape measurement was performed with a single point triangulation probe connected to a National Instrument data acquisition card. The acquisition rate is 200 samples per second. After each forming iteration, the plate was scanned along the y-axis every 15mm and the shape data recorded continuously to determine the shape of the plate, from which the shape residual could be calculated.

Initially, the implementation of the finite element method in the iterative laser forming procedure was validated by forming pillow and saddle shapes from plane plates of uniform thickness: these results are not presented here. For laser straightening of the friction stir-welded AA2024T3 plates, the plates typically had a saddle shape with a maximum deflection of 4.1 mm at the beginning of the ILF process. A typical initial shape is shown in **fig. 3 (top-left figure)**. After 6 iterations the distortion of the plate was reduced considerably and had a maximum deflection of 0.94 mm in the right upper corner ($x = 0.185$ m & $y = 0.125$ mm, for origin at the plate centre). The final root mean square (rms) error was 0.3 mm (compared to 2.15 mm rms at iteration 0) and the error between the measured shape and the Legendre

polynomial fit was approximately 0.13 mm rms. The final curvatures are reported in **table 1**. and should ideally be equal to zero for the straightened plate.

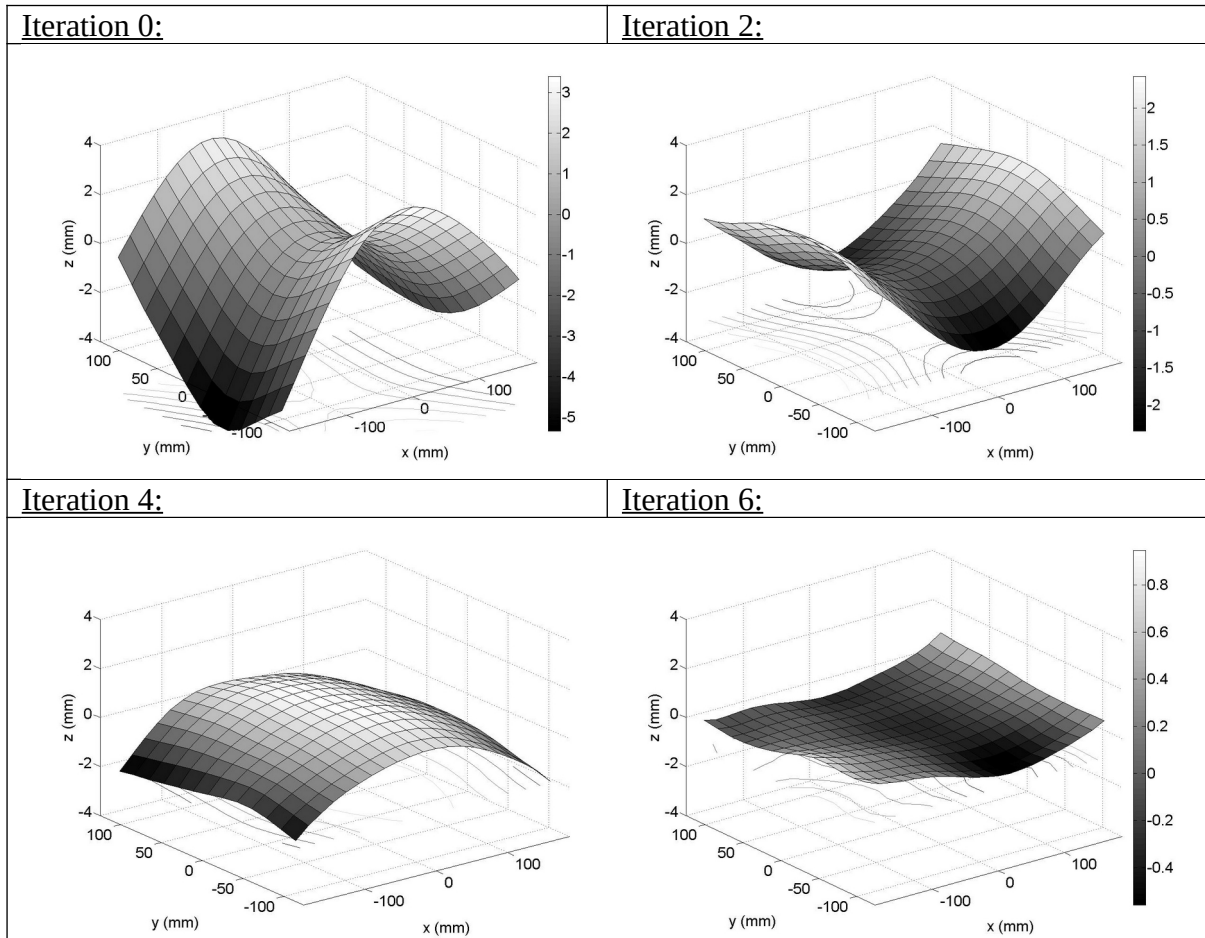


Figure 3: Laser straightening evolution of stir-welded AA2024T3 plate after one top and bottom laser treatment.

Table 1: final results for laser straightening of stir-welded plates

	RMS error (mm)	Leg. Error* (mm)	kx (1/m)	ky (1/m)	kxy (1/m)
Straightening	0.3	±0.13	-0.02	0.57	0.37

*Error on the Legendre polynomial shape description;

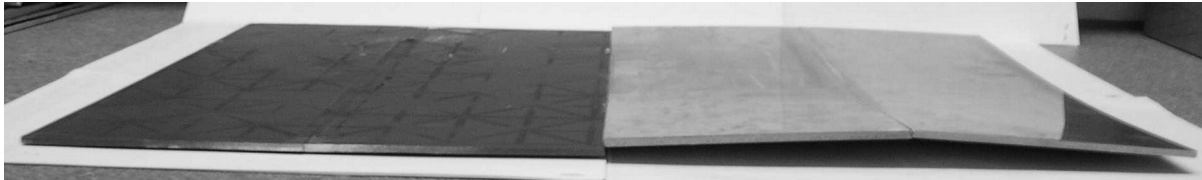


Figure 4: Picture of the straightened (left) and original (right) stir-welded plate.

5. Discussion of Results

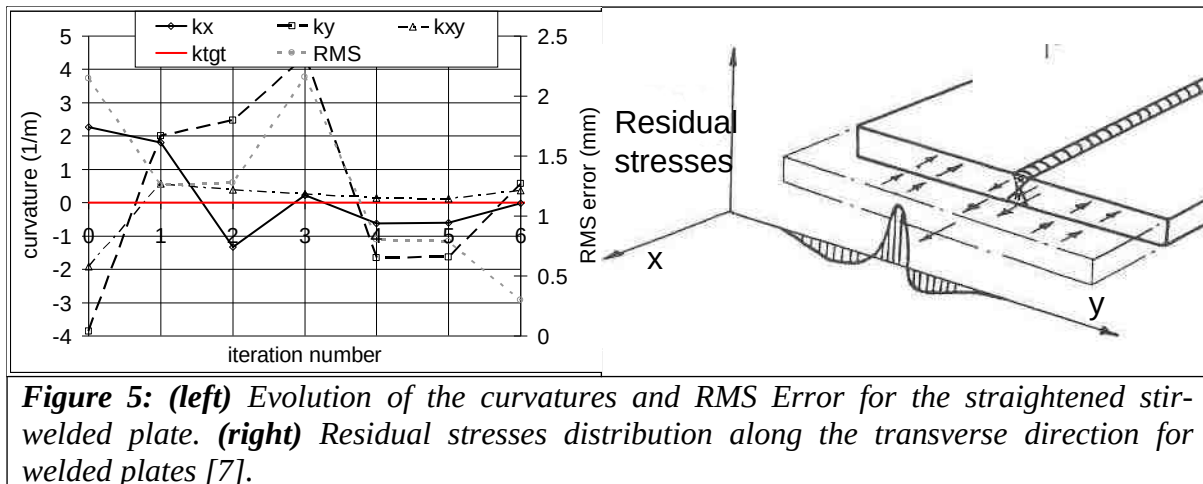


Figure 5: (left) Evolution of the curvatures and RMS Error for the straightened stir-welded plate. (right) Residual stresses distribution along the transverse direction for welded plates [7].

Firstly the effect of residual stresses on the accuracy of the final shape will be discussed. It is assumed in the iterative laser straightening (ILS) process that the friction stir-welded plate was residual stress free at each iteration which is clearly not the case. **Fig. 5-left** shows the curvature evolution of the straightened welded plate after each iteration of the forming process. The target curvature is zero in each direction. During the first two iterations the ILS process reduced the curvatures leading to a decrease of the RMS error. However, after the third iteration the y-curvature varied strongly taking the values 4.4 m^{-1} then -1.6 m^{-1} . The typical transverse residual stress distribution (perpendicular to the weld line), **fig. 5-left**, varies along the y-axis (tensile then compressive) whilst it is constant in the x-axis. The change in y-curvature could be due to the heating of the plate during the ILS process releasing the residual stresses and generating larger changes in the y-curvature than in the x-curvature.

Secondly, it was found that after the fifth iteration, the membrane strain required from the shape residual was smaller than the bending strain, and no scan was required on the lower surface.. This fact is in good agreement with shell theory that predicts the dominance of the membrane strain over the bending strain when the plate deflection is greater than the plate thickness. The membrane strain required to produce the shape residual at the start of the process (maximum plate deflection of approximately 4.1 mm) is shown in **fig. 6-left**, The membrane strain required at iteration 6 is shown in **fig. 6-right** and is smaller than the

required bending strain (not exhibited) which was around 1.6×10^{-3} at iteration 0. Hence forming due to the membrane strain is favoured at the start of the ILS process, followed by bending strain to finish the process.

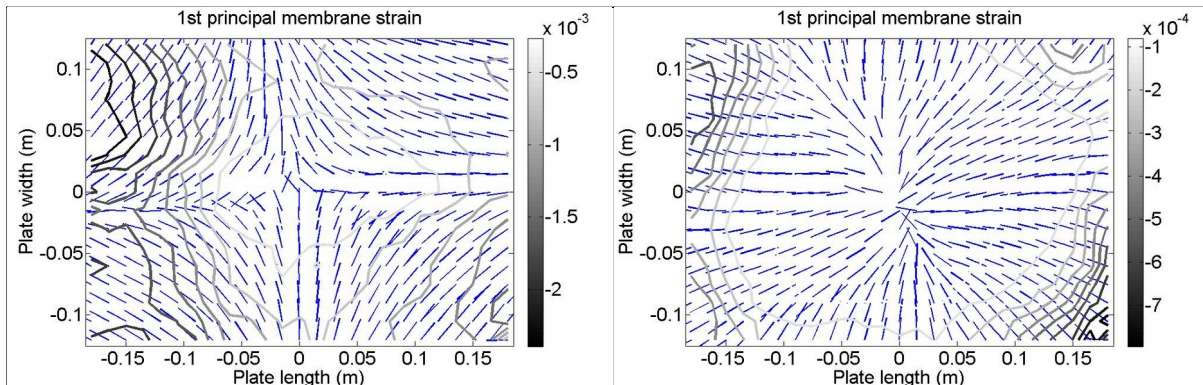


Figure 6: 1st principal membrane strain values (on the left at iteration 0, on the right at iteration 6). Remark: average principal bending strain values (absolute value) along the iterations were from 1.6×10^{-3} to 4×10^{-4} .

6. Conclusions

In this work, we presented an iterative laser straightening procedure that incorporated a finite element model in order to estimate the required membrane strain was presented. Straightening was achieved successfully on friction stir-welded AA2024T3 plates with a typical distortion of 4 mm. The final maximum distortion was below 1 mm with an rms error around 0.3 mm. A slight asymmetry perpendicular to the direction of the weld line was noted and was attributed to the release of residual stresses generated by the welding process. The knowledge gained from the iterative straightening of plane plates using a finite element model should enable us to investigate more complex welded structures such as plates with varying thickness or welded plates with different materials.

Acknowledgements

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