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# Straightening of Distorted Welded Plates by Iterative Laser Forming

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## Abstract:

An iterative approach to laser forming gives the ability to measure the shape after each stage of forming and therefore vary subsequent processing conditions to converge on the desired shape without the need for extreme levels of accuracy in material characterisation and process modelling. Three-dimensional laser forming of non-developable surfaces brings along the need for an accurate model of both the bending and membrane strain necessary to form the shape of interest. We report a new approach to iterative laser forming of non-developable surfaces, defined as surfaces with non zero Gaussian curvature (e.g. pillow or saddle), where the required membrane strain is calculated from a finite element simulation. The laser scan pattern and heating distribution is applied on the specimen in form of a fixed scan lattice. This forming approach has been used not only to form pillow and saddle shapes but also to straighten friction stir-welded AA2024T3 plates. To the best of our knowledge, this work represents the first iterative laser correction of distorted welded structures.

Keywords: laser forming (straightening), surface treatment, iterative approach, finite element simulation, distorted welded plates.

## 1. Introduction

A common problem in industry is the unwanted distortion after welding caused by the non-uniform heating of the material during welding. This in turn produces plastic strains and residual stress due to the mismatch of thermal expansion in the weld and surrounding material. Therefore post-process correction of such distortions is of great interest for numerous sectors of industry. In particular, an iterative approach in laser forming could be a promising process for the straightening of such distorted welded plates because highly accurate material characterisation and process modelling is not required.

Extensive studies have been carried out to understand laser forming mechanisms and they show that the process is based on the introduction of thermal stress including plastic strains which result in bending and/or shortening the material (temperature gradient mechanism) or produce a local buckling (buckling mechanism) [1]. In order to further control and understand the laser forming process Vollertsen stated a simplified two-layer model that described the dependence of bend angle on control parameters such as laser power, scan speed and material parameters. The model was extended [2] using a residual stress approach that requires calibrated values of the maximum plastic strain at the surface and the extent of the plastic zone.

McBride et al [3] developed a combined numerical-analytical model that relates the bend angle (and shrinkage) to laser line energy which is defined as a fraction of laser power and scanning speed. It shows the characteristic behaviour such as the functional form of the bend-angle-line-energy curve, including line energy threshold, roll-off and its dependency on the laser beam diameter. In addition, the model predicts

that through the choice of line energy and interaction time either bending or in-plane strain is favoured.

For laser forming of non-developable surfaces not only is an accurate model of both bending and membrane strain required but also the calculation of the laser scan paths and heating conditions. Finite element process simulation has been used to determine the required strain field for pillow and saddle shapes and to decompose strains into bending and membrane strains. This approach has been first developed for flame bending process [4] in form of single pass forming. It has been extended to the laser forming process with a complete process design [5].

Later on McBride et al [6] developed an iterative approach for laser forming where principal curvatures and principal membrane strains are decomposed along a four-direction fixed laser scan lattice, rather than forming along lines of principal curvature and strain. In order to calculate the required bending and membrane strain after each iteration, an analytical model was used.

For an extension of our iterative laser forming approach described in [4], future work would include the forming of non-developable surfaces with plates of varying thickness. Since there would be some difficulties to calculate the required strain distribution for varying thickness plates with the analytical model, the finite element method was incorporated in the iterative laser forming process.

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 overall strategy of the iterative laser forming is shown in figure 1. The process is based on four main steps and aims to compare the current to the target shape in order to produce the required strain field in term of curvature and membrane strain. Both are determined independently and the membrane strain is calculated by a finite element simulation, described in more detail in the next section.

The first step is to define the measured and target shapes in terms of gradient and curvature by using a polynomial fit to approximate the plate surface of current and target shape.

Secondly, changes in curvature ( $\Delta\kappa$ ) and membrane strain ( $\Delta\varepsilon$ ) are determined which are required to transform the current shape into the target shape. The required membrane strain  $\varepsilon$  is calculated with a finite element simulation. Independent from this, curvatures of measured and target shapes are calculated by taking numerical second derivatives of surface heights over a pre-defined x-y grid and subtracting to determine the curvature change  $\Delta\kappa = \kappa_0 - \kappa$ . This step involves a mathematical correction of the membrane strain field by a radially-varying compatible strain field to remove all tensile strains, because only compressive membrane strains can be generated by laser forming.

The third step is to project the required curvature and strain field distribution onto a scan grid, which has four fixed scan directions in order to simplify the scan line geometry and strain history.

The fourth step is to calculate the heating conditions (fixed laser power, fixed laser beam diameter and variable laser scan speed) from an experimental calibration database for bending and membrane strain [3, 6], shown in figure 2. In order to determine the line energy for the required bending and membrane strain a linear approximation to the working region of the measured bending and shrinkage calibration curves has been applied. The laser scan speed as the final control

parameter for the heating conditions is finally generated as a G-code file to automatically drive the CNC controller over the fixed forming scan lattice.

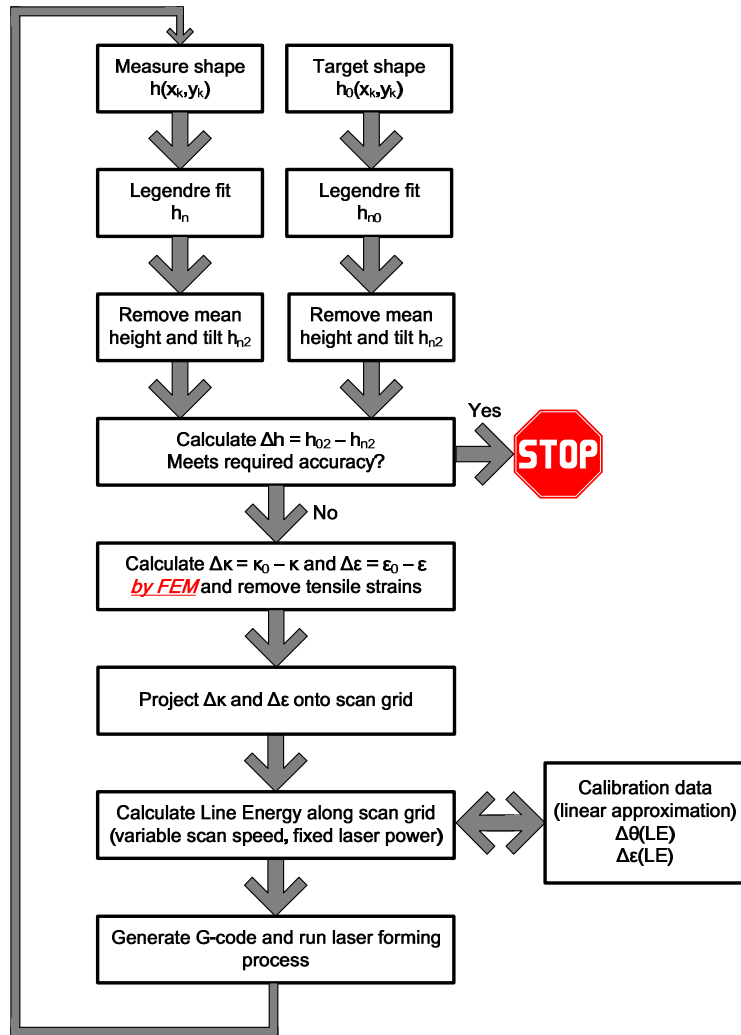


Figure 1: Iterative laser forming strategy

Currently the 'bending' scan is applied first on the top surface of the plate. After that the plate is flipped over and the 'membrane' scan is applied on the bottom surface of the plate, which provides an accurate and stable solution [6].

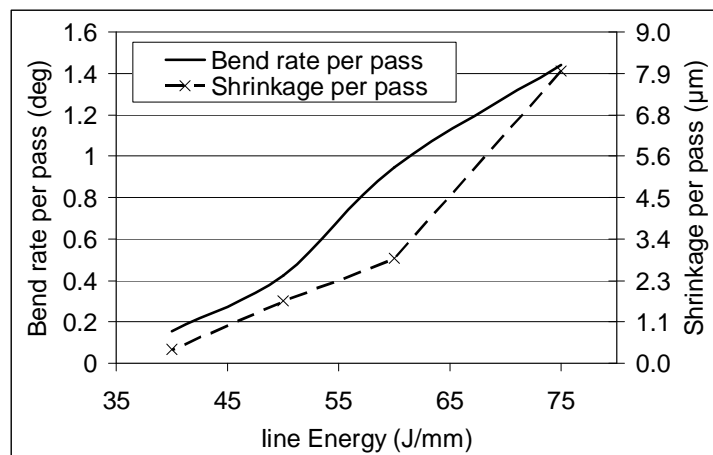


Figure 2: Shrinkage and bend angle versus line energy (Calibration data)

### 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 residual deflection  $\Delta h$  defined as the difference between current shape and target shape after each iteration is the input for the FE-simulation, which is carried out with the software Comsol, because of its compatibility with Matlab.

The use of a complete thermo-mechanical simulation would take too long to run between the forming iterations. Therefore, some simplifying assumptions were 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 4<sup>th</sup> 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 an AMD bi-processor (2GHz) with 2 GO memory. As described previously, to the membrane strain distribution as an output of the FE-simulation, a compatible strain field was added in order to remove all tensile strains.

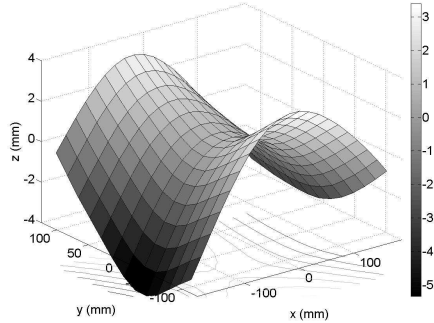
### 4. Experimental straightening of friction stir-welded plates

The laser used for the experiments was a TRUMPF TLF 2700 Turbo, a 2.7kW CO<sub>2</sub> 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 as follows: laser power fixed at 1000W and a laser beam diameter of 9 mm. The laser scan speed varied along the lattice scan to provide line energies in the range of 35 J/mm to 75 J/mm. The friction stir-welded AA2024T3 specimens measured 370 mm x 250 mm x 3 mm and were supplied by BAE SYSTEMS. The plates were cleaned and then coated with graphite to enhance the absorption of the laser heat flux. The shape measurement was performed with a single point triangulation probe connected to a National Instrument data acquisition card. The acquisition rate was 200 samples per second. After each forming iteration the plate was scanned along the y-axis in lines of 15mm spacing. The shape data was recorded continuously to determine the deflection of the plate from which the shape residual could be calculated.

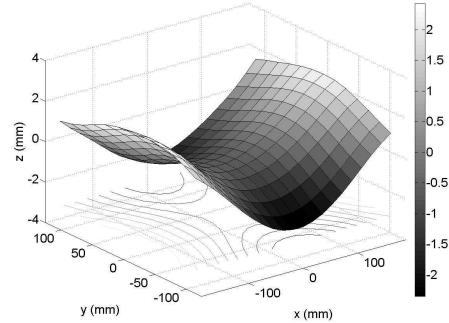
Initially, the implementation of the finite element method in the iterative laser forming procedure was validated by forming pillow and saddle shapes with plates of uniform thickness; these results are not presented here. For laser straightening of the friction stir-welded AA2024T3 plates, the initial shape of the plates was similar to a saddle shape with a maximum deflection of 4.1 mm before the first iteration of the ILF process. A typical initial shape is shown in figure 3 (iteration 0). 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, reference is the plate centre). The final root mean square (RMS) error was 0.3 mm (compared to 2.15 mm RMS at iteration 0).

The 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 shown explicit in table 1. For a perfectly straightened plate they should be equal to zero.

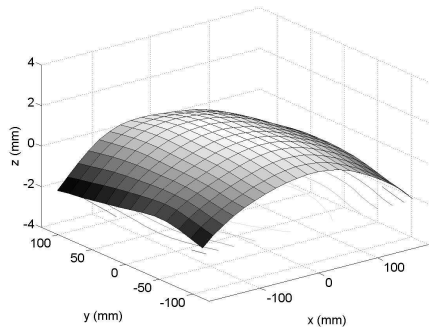
Iteration 0:



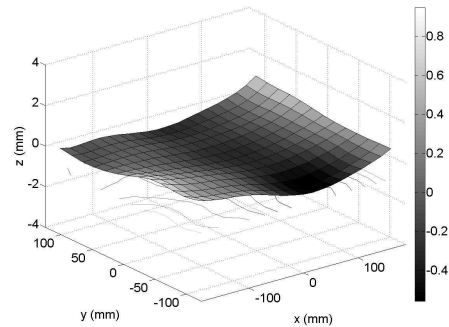
Iteration 2:



Iteration 4:



Iteration 6:



**Figure 3:** Evolution of the shape during the ILS process

Iteration 0: Initial shape after welding process

Iteration 2: Shape after one top and one bottom scan

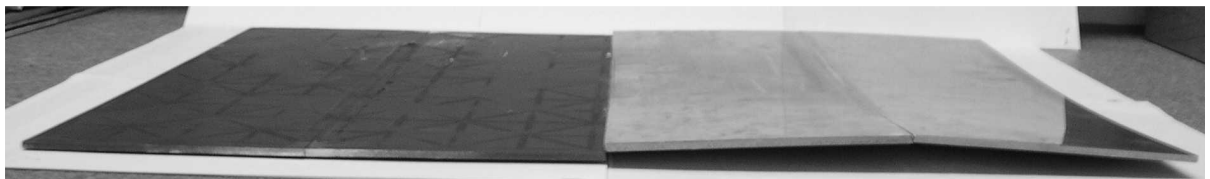
Iteration 4: shape after two top and two bottom scans

Iteration 6: final shape (after two bottom and four top scans)

**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

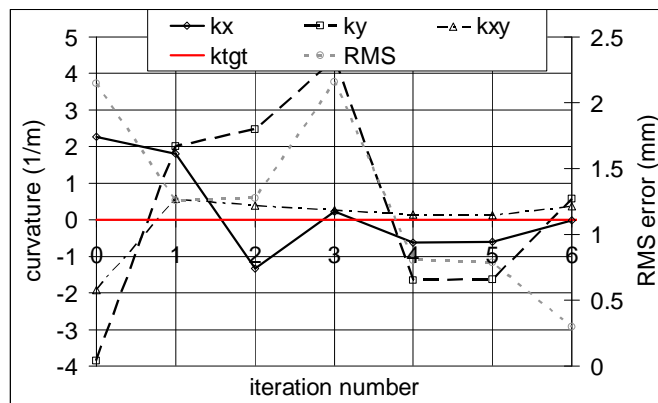
\*Error on the Legendre polynomial shape description;



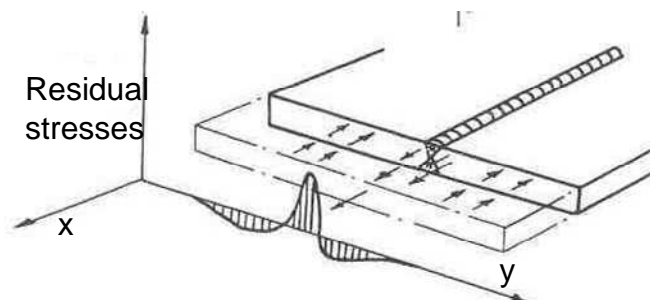
**Figure 4:** Picture of the straightened (left) and original friction stir-welded plate (right)

## 5. Discussion of Results

Firstly the effect of residual stresses on the accuracy of the final shape will be discussed. An assumption for the iterative laser straightening process was that the friction stir-welded plate is residual stress free which is clearly not the case. Figure 5 shows the curvature evolution of the straightened welded plate for each of the six iterations of the forming process. The target curvature is zero for both directions. During the first two iterations the iterative laser straightening process reduced the curvatures leading to a decrease of the overall RMS error. However, after the third iteration the  $y$ -curvature varied strongly taking the values  $4.4 \text{ m}^{-1}$  then  $-1.6 \text{ m}^{-1}$  whilst it is constant along the  $x$ -axis. The change in  $y$ -curvature could be due to the heating of the plate during the ILS process which releases residual stresses from the pre-process of friction stir-welding. It is known that during the welding process, because of non-uniform heating, residual stresses are created, most significantly perpendicular to the weld line. Figure 6 shows the characteristic transverse residual stress distribution after welding (perpendicular to the weld line). It varies along the  $y$ -axis starting with large tensile stress in the weld which then decreases and turns into compressive with increasing distance to the weld. The release of these residual stresses due to the thermal interaction of the laser beam would clearly affect the evolution of the  $y$ -curvature to a larger extent than the one of the  $x$ -curvature. This might be a possible explanation for this phenomenon.



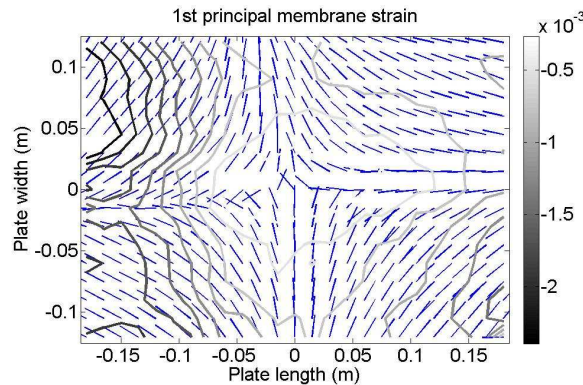
**Figure 5:** Evolution of the curvatures and RMS error for the straightened friction stir-welded plate



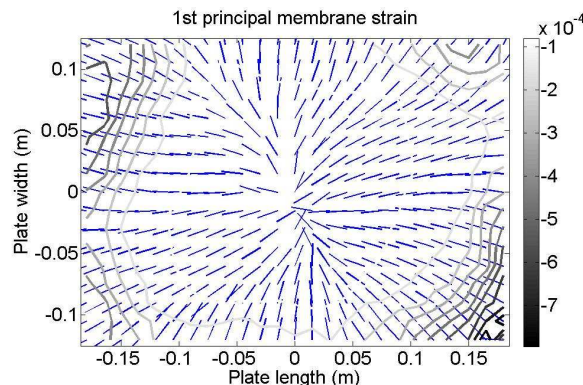
**Figure 6:** Residual stress distribution along the transverse direction for welded plates taken from [8]

Secondly, it was found that after the fifth iteration, the membrane strain calculated from the finite element simulation to from the shape residual was smaller than the bending strain and below forming threshold. Therefore no scan was required on the lower surface and during iteration 5 and 6 a bending scan was applied on the top 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 figure 7. The membrane strain required at iteration 6 is shown in figure 8 and is smaller than the required bending strain (not exhibited) which was around  $1.6 \times 10^{-3}$  at iteration 0. Due to this fact membrane strain is favoured at the start of the ILS process when the deflection is greater than the plate thickness (large deflection). With subsequent iterations the deflection decreases and therefore small deflection theory becomes valid for the process which favours bending strain over membrane strain.



**Figure 7:** 1<sup>st</sup> principal membrane strain at iteration 0 (absolute value)



**Figure 8:** 1<sup>st</sup> principal membrane strain at iteration 6 (absolute value)

## 6. Conclusions

In this work, an iterative laser straightening procedure that incorporates a finite element model was presented in order to estimate the required membrane strain. Straightening was achieved successfully on friction stir-welded AA2024T3 plates with a typical distortion of around 4 mm. The final maximum distortion after 6 iterations was below 1 mm with an RMS error of about 0.3 mm. A slight asymmetry perpendicular to the direction of the weld line was noted and has been 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 of varying thickness or welded plates with different materials.

## Acknowledgements

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