Feedback control of laser forming using flattening simulations for error determination

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Abstract. Laser forming is a non-contact forming method. By control of different process parameters, different forming mechanisms can be achieved. The forming mechanisms allows for bending, compression and buckling. Process control to ensure correct combination and usage of each forming mechanism is still an open issue. Present work is an attempt to implement a feedback control loop using measurements of the current shape between laser scan pass. This work presents an initial case study used to evaluate a feedback control loop. A flattening model is used to determine the difference in strains between a target shape and the current shape. The current shape is updated between laser scan paths. The case study examines different shapes including the dome, saddle and v-bend shapes. By examining different shapes that require different forming mechanisms, this work takes steps toward formulating process design principles for use in feedback control of laser forming. The results show decent agreement with the target shape and the formed shape for the v-bend. As the cases increase in complexity, requiring a combination of forming mechanisms, the disagreement increases. The analysis of the process indicates that the boundary conditions of the flattening model and the design of the controller could be improved to reduce tolerances.

1. Introduction
Laser forming is a method for forming shapes without the need for external forces or component specific tools. The shape is formed by thermal distortion induced by heating with a laser. This allows a flexible approach where different shapes can be made without the need for physical changeover. While the process shows great promise, process control is still an open issue. Process control of laser forming can typically be classified as open loop or closed loop planning and as 2D or 3D planning.

The open loop approach means planning the full process beforehand while closed loop involves making corrections during forming, usually involving a form of measurements of the geometry. 2D control is typically used for creating v-bended shapes. The process parameters include the distance between parallel line scans and the heat input along these lines. Various methods have been proposed for 2D process planning. Among them are a response surface methodology [1], geometric information [2, 3], genetic algorithms [4], bending angle [5] and curvature [6]. Four of these have implemented some form of closed loop planning [1, 3, 5, 6]. For 3D process control the different methods are based on a strain analysis [7–13], an inverse analysis [14] and geometric information, based on differences in height or angle [15]. The authors of [16] uses differences in the bending angle. The authors of [10,11,15] comment on the need for a closed loop approach. The authors of [16] use feedback control.
Present work is an attempt to investigate the laser forming process and feedback control on the three cases seen in figure 1. The work builds on the overall consensus of using a strain analysis for 3D planning but with using feedback control to update the process settings. This paper uses a flattening simulation in the commercial FEM software LS-DYNA® to calculate the strain fields. The strain fields are compared at each iteration to generate an error field. The error field is used to calculate new laser scan lines and process settings. The feedback loop is applied to three different cases to increase process understanding. The initial shape is found by flattening of the target shape.

Figure 1. The complexity of the mechanisms to make the bends are increased from (a) one sided linear bending (b) one sided bending and compression and to (c) double sided bending and compression.

2. Feedback control
The feedback control is built on two different laser forming mechanism, namely the temperature gradient mechanism (TGM) and the upsetting mechanism (UM) [17, 18]. Laser forming is based on creating a thermal expansion of the material due to localized elevated temperatures. The localized thermal expansion is restricted by the surrounding material, which can introduce permanent compressive strains in the component. TGM is a mechanism describing a temperature gradient through the thickness, which creates compressive strains at the upper surface of the component. This causes a bending behavior and TGM is therefore associated with bending. UM is a shortening mechanism, which is achieved by ensuring an even temperature distribution through the thickness. This causes evenly distributed compressive strains through the thickness which results in a shortening of the component, causing UM to be associated with a membrane behavior.

2.1. Error field
Assume a given mesh with n vertices, \( v_i \) for \( i = 1..n \). For each vertex an error, \( e_i \), is calculated using the strain fields. To account for TGM and UM, the error used in this work is split between a membrane error, \( e^m_i \), to account for shortening of the material (UM), and a bending error, \( e^b_i \), to account for bending of the material (TGM). Each error is a 2D tensor with two corresponding principle values (\( k_1 \) and \( k_2 \)) and principle directions (\( \lambda_1 \) and \( \lambda_2 \)) which lie tangent to the surface.

\[
e_i = \begin{bmatrix} k_1 & 0 \\ 0 & k_2 \end{bmatrix} \quad \lambda_i = [\lambda_1 \lambda_2]
\] (1)

2.2. Strain estimation
The strains are estimated using flattening. The strains required to develop the target shape and current shape are found by pressing them flat in a finite element model. By comparing the strain fields of the current shape with the target shape, the difference in strains are to be induced by
the laser forming process. Laser forming is a non-unique path independent incremental forming mechanism, and it should be noted that the flattening model finds a specific path dependent strain field that is based on the chosen boundary conditions. This discrepancy is not necessarily a concern, as long as the found strain field is a possible solution that can be reproduced by laser forming. This means that the method presented is not dependent on the specific flattening model used, which could be replaced without changing the overall methodology. It cannot, however, be excluded that an optimal error field exist. A requirement of any error field is that it is able to capture the mechanisms, bending and membrane, required to go from current shape to target shape.

The membrane strains are defined as the strains at the center of the material, halfway through the thickness, $\varepsilon_{\text{center}}$, while the bending strains are defined as the difference between top, $\varepsilon_{\text{top}}$, and membrane strains. With the top of the surface being the surface initially placed toward the laser.

$$
\varepsilon_m = \varepsilon_{\text{center}}, \quad \varepsilon_b = \varepsilon_{\text{top}} - \varepsilon_m
$$

To calculate the error, the strain field of the target shape is subtracted from the current shape using a bijective mapping.

$$
e_{\text{m}*} = \varepsilon_{\text{current}} - \varepsilon_{\text{target}}^m, \quad e_{b*} = \varepsilon_{\text{current}} - \varepsilon_{\text{target}}^b
$$

Where $e_{m*}$ and $e_{b*}$ are symmetric tensors, the * is used to denote that they are not necessarily diagonal. The principal values of $e_{m*}$ and $e_{b*}$ along with the principle directions $\lambda_j$ and $\lambda_m^j$ for $j = 1, 2$ are used for path planning.

### 2.3. Path planning

The path, can be calculated using the equation of motion, see equation (4).

$$
p(t) = p(0) + \int_0^t k_j(t)\lambda_r(t)dt, \quad j \neq r
$$

Where $p(t)$ is the path of the laser and $p(0)$ is the starting point of the path planning routine. The choice of $k_j$, with $j = 1, 2$, depends on the chosen convention for the tensors. The direction of the path $\lambda_r(t)$, with $r = 1, 2$, should be perpendicular to the direction of the principle error, This equation can be solved using Euler’s method for both membrane and bending on both sides of the surface. A set of rules for the path planning can be established to both simplify the path planning and filter the paths. The following constraints are used in present work:

- **Threshold error** - An area is ignored if the error is below a threshold value, $|e_{b\text{min}}|$ and $|e_{m\text{min}}|$, for the bending and membrane error respectively. This is to reduce the risk of overshooting the target shape.

- **Threshold path** - Once a path has been planned, the same area, using the diameter, is thresholded from new paths for this planning iteration. This is to avoid planning multiple paths on top of each other. Once a new planning iteration starts, the threshold is reset.

- **Threshold length** - If the length of a path is below a threshold value, $|p|_{\text{min}}$, the path is discarded to favor longer paths.

### 2.4. Controller

The controller is responsible for assigning the positions found by the path planner with relevant laser forming process settings. The controller used in this work is based on control of the speed of the laser. The speed is dependent on the laser forming mechanism. Therefore two controllers of the same design with different settings are used in present work, one for TGM and one for UM.
Given a discrete set of \( l \) points \( p_l \) with \( l = 1..h \) that form a path planned by the path planning routine. The speed is determined using an inverse distance weighting method to interpolate the error between vertices. Given a laser scan speed limit of \( [v_{\text{min}}, v_{\text{max}}] \), the speed is found using a gain factor \( c \). The used controller settings can be seen in table 1. The settings were found empirically as design guidelines are not yet formulated.

\[
v_l = \begin{cases} 
v_{\text{min}} & \text{if } v_{\text{max}} - ck_l < v_{\text{min}} \\ v_{\text{max}} - ck_l & \text{otherwise} \end{cases}
\]  

(5)

Using a constant gain factor as well as using a minimum error as a threshold value for the path planning, means that a stationary error is expected. Therefore a form of integration is implemented in present work to improve tolerances in case no path is found meaning the process would otherwise stop. The integration is a simple weight which is multiplied to the entire error field for both the path planning and controller. The integration is iteratively used to increase the error field until new paths can be determined.

To stop the control loop, the tolerance is computed for each vertex. The tolerance is defined by the geodesic distance between a vertex on the current shape and the target shape. The tolerance allows the computation of a forming percentage defined as the sum of tolerances of the current shape over the sum of tolerances of the initial shape. The feedback control loop stops once no improvement in the forming percentage has been registered three times in a row resulting in divergence or if the maximum tolerance is below a threshold of 1 mm resulting in convergence.

Table 1. The controller settings used in present work. Upsetting is achieved by heating both sides, one after the other, with the settings given in the table.

| Parameter       | Value | Unit     | Parameter       | Value | Unit     |
|-----------------|-------|----------|-----------------|-------|----------|
| \( v_{\text{max}} \) | 6,000 | mm/min   | \( v_{\text{max}} \) | 800   | mm/min   |
| \( v_{\text{min}} \) | 3,000 | mm/min   | \( v_{\text{min}} \) | 600   | mm/min   |
| \( c \)         | 50,000| mm/min   | \( c \)         | 20,000| mm/min   |
| Laser diameter  | 3     | mm       | Laser diameter  | 2     | mm       |
| Laser power     | 320   | W        | Laser power     | 50    | W        |

3. Method
3.1. Laser forming simulation
The simulations are based on a coupled thermal and mechanical implicit analysis. Each pass of the laser is modeled as a separate simulation with the stresses, strains and temperature distributions used as inputs for the following simulation. The model uses shell element formulation -16, which is a fully integrated shell element [19]. The shell elements use varying temperature through the thickness with 7 integration points to ensure a through the thickness temperature gradient. The thickness of the three cases are set to 0.5 mm. The material is an elastic-plastic material with temperature dependent material properties. The laser is modeled as a surface flux with no penetration using a Gaussian distribution. The thermal boundary conditions include radiation and convection of the surface. Clamping is added separately for the three parts. For the v-bend, all nodes at one end at \( y = 0 \) mm are clamped. For the saddle and the dome, three nodes in the center of the part are clamped. A constant temperature at the clamped nodes of 20°C is used to simulate a near constant temperature at the clamp. As most
of the deformation occurs at elevated temperature [20], a numerical sensor is used to stop the simulation once the maximum node temperature reaches 220°C to reduce simulation time.

3.2. Flattening simulation

The flattening is performed using an explicit time scaled mechanical analysis. The shape is pressed flat between an upper and lower rigid plate. The lower plate is fixated, while the upper tool is velocity controlled with ramp up and ramp down. The shape is input slightly above the lower plate, with significant space to the upper plate. The upper plate is translated towards the shape at the beginning of the simulation to ensure contact to reduce the simulation time. Symmetry planes are used to fixate the shapes between the plates. The flattening simulation used element formulation 17, which is a fully integrated DKT element [19]. As previously described, the flattening simulation generates a path dependent strain field based on the chosen boundary conditions. Analysis on the variation between different element formulations and boundary conditions are left as further work.

4. Results

4.1. V-bend

The v-bend is considered the simplest shape as it only requires TGM to develop. The forming percentage as well as the maximum tolerance can be seen in figure 2a, which shows that the feedback loop iteratively improves the tolerances to below the target tolerance with a final maximum tolerance of 0.88 mm < 1 mm.

![Figure 2](image)

**Figure 2.** Results of the v-bend. (a) The forming percentage at each iteration. The bending error ($k_b^2$) and path planning with colored paths; blue for TGM, black for UM at (b) iteration 0 and (c) iteration 19. (d) the tolerances at each vertex for iteration 20.

Figure 2b shows the value of $k_b^2$, which is used for the planning of the bends. The laser scan paths are intuitive to what is expected, several straight lines perpendicular to the bending. As
the shape approaches the target shape, the error reduces, as can be seen in figure 2c, which shows the last iteration before the final shape is reached. $k_2^b$ has clearly been reduced, showing that the error determined from the flattening simulation can be used to plan the paths. The final shape can be seen in figure 2d, which also shows the tolerance. Figure 2d shows signs of edge effects around the edges of the bend [18]. The tolerances are comparable to other work within laser forming [10–13], but requires improvement before it can applied in industry. A limiting factor is the numerical noise of the flattening simulation evident in figure 2c. The numerical noise makes small corrections difficult if the noise exceeds the size of the error, $k_2^b$. Reducing the numerical noise requires a deeper investigation into the flattening model and the comparison of different models.

4.2. Dome

The dome shape is more complex compared to the v-bend as it requires both mechanisms to develop. The results of the dome shape can be seen in figure 3. Figures 3b and 3c show the membrane error, which is required to develop the shape. The initial planned paths can be seen in figure 3b, which shows the TGM paths (in blue) and the UM paths (in black). The TGM paths appear randomly orientated, which is due to the spherical nature of the dome. The spherical nature of the dome means that the bending is similar in all directions and the resulting paths become randomly oriented. The UM paths on the other hand are systematically from the corners, which is consistent with the notion that the material must compress to avoid wrinkling in order to achieve the dome. The control loop stops due to a divergence of the forming percentage, as evident in figure 3a, with a maximum tolerance of 4.2 mm. The final attempts to improve the shape can be seen in figure 3c. Figure 3c also shows a fold of the corner at $x =
0 mm, y = 40 mm, this may be more visible in figure 3d. The fold reveals a potential pitfall of laser forming, that the induced strains caused by the laser result in undesired deformations elsewhere on the shape. One of the limiting factors in the process planning is how the laser scan paths and their strain contribution contribute to subsequent passes. In this case, the folding is likely caused by insufficient upsetting at the corner coupled with the induced strains elsewhere in the component. The automatic control and planning of using both TGM and UM requires more work. However, the method shows that it is possible to extract and plan based on information from the strain field in a feedback loop. Strategies for avoiding locking the shape in undesirable shapes likely require more complex control strategies than currently presented.

4.3. Saddle

The results of the saddle shape can be seen in figure 4. Figures 4b and 4c show the membrane error, $k_m^2$, as well as the paths for TGM (in blue) and UM (in black). The TGM paths are structured in the two primary directions denoted by x and y which correlates to the saddle being a combination of bending about these two axes. The TGM paths in the x direction in figure 4b are applied to the lower surface. The UM paths in black, are concentrated around middle of the borders (x,y = 0, -20 and x,y = 0, 20 etc.). This strategy appears successful when examining the tolerances of the final shape in figure 4d. However the feedback loop is unable to achieve the target tolerance of 1 mm and stops due to a divergence of the forming percentage, with a maximum tolerance of 2.3 mm. However, no undesired folds are created compared with the dome shape. This can mainly be attributed to the more ordered planning of the TGM paths for the saddle shape, which reduces the possibility of undesirable deformations resulting in locking of the shape.

![Figure 4](image-url)
5. Discussion
The presented control strategy is still at an early stage and several improvements are of interest.
As previously discussed, the flattening simulation directly influence the controller. Limiting
factors include the time consumption of the flattening simulation, which directly affect the total
processing time, and the choice of boundary conditions, which affects the quality of the error
field. Factors to increase the quality of the simulation, such as different element formulation
and mesh size also generally increases simulation time. An example of the time consumption;
the flattening simulation takes approximately 3-5 minutes per iteration for the shapes used in
the present work. An interesting alternative to the flattening simulation is the use of direct
approaches [12,13]. These avoid the time dependency of the simulation by direct comparison of
the shapes [21]. A direct approach results in a reduced processing time, however, the quality of
the error field requires further investigation.

6. Conclusion
The use of feedback control for the laser forming process has been investigated based on the three
geometrical cases, a v-bend, a dome and a saddle shape. The feedback loop is based on flattening
simulations to produce an error field. A path planning strategy and simple controller design
has been presented and shown to be able to reduce the error field. The results indicate good
agreement for a v-bend and the saddle while the dome shape require additional improvements
to avoid locking. Two areas of modifications for further work have been identified. The first is
the flattening simulation which is dependent on the chosen boundary conditions. Furthermore
the flattening simulation is time consuming as it requires several minutes at each iteration,
directly affecting total processing time. The second area is controller design, which includes
both controller design itself and guidelines for choices of controller settings.

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