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Developments towards controlled three-dimensional laser forming of continuous surfaces

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There has been a considerable amount of work carried out on two-dimensional laser forming, using multipass straight line scan strategies to produce a reasonably controlled bend angle in a number of materials, including aerospace alloys. However, in order to advance the process further for realistic forming applications and for straightening and aligning operations in a manufacturing industry it is necessary to consider larger scale controlled three-dimensional (3D) laser forming. The work presented in this article uses a predictive and adaptive approach to control the 3D laser forming of a 1.5 mm mild steel sheet into a desired continuous surface. The surface considered in the study was the pillow (or dome) shape. Key to the control of the process was the development of a predictive model to give scan strategies based on a required geometry. The forming rate and distribution of the magnitude of forming across the surface were controlled by the process speed. When the geometry is not formed within one pass, an incremental adaptive approach is used for subsequent passes, utilizing the error between the current and desired geometry to give a new scan strategy, thus any unwanted distortion due to material variability can be accounted for. © *2005 Laser Institute of America.*

Key words: laser forming, laser bending, mild steel, nondevelopable surfaces, 3D

I. INTRODUCTION

The laser forming process (LF) has become viable for the shaping of metallic components, as a means of rapid prototyping and of adjusting and aligning. Laser forming is of significant value to industries that previously relied on expensive stamping dies and presses for prototype evaluations. Relevant industry sectors include aerospace, automotive, shipbuilding, and microelectronics. In contrast with conventional forming techniques, this method requires no mechanical contact and thus promotes the idea of "virtual tooling." It also offers many of the advantages of process flexibility and automation associated with other laser manufacturing techniques, such as laser cutting and marking.[1]

The process employs a defocused laser beam to induce thermal stresses without melting in the surface of a workpiece in order to produce controlled distortion. These internal stresses induce plastic strains, bending or shortening the material, or result in a local elastic plastic buckling of the work piece depending on the mechanism active.[2] LF can be used for two-dimensional (2D) and three-dimensional (3D) forming. 2D laser forming encompasses laser forming operations that utilize two-dimensional out-of-plane bends to produce three-dimensional results, e.g., a fold. 3D laser forming encompasses laser forming operations that can utilize combinations of multiaxis two-dimensional out-of plane bends and in-plane localized shortening to produce three-dimensional spatially formed parts, e.g., a dome.

In order to advance the laser forming process for realistic forming applications and for straightening and aligning operations in a manufacturing environment, it is then necessary to consider 3D laser forming. Less work has been completed in this field compared to 2D LF, however, the process has been shown to have a great deal of potential. In order to compete directly with conventional forming techniques though, such as die forming, the process must be proven to be reliable, repeatable, cost effective, and flexible. It is the potential flexibility of 3D laser forming that offers the greatest benefits. A change to a required part geometry could be implemented easily through the computer aided design (CAD) driven process, this can be compared to the expensive and in-flexible hard tooling requirements of the die forming process. The work presented here on 3D laser forming aims to prove the viability of this technique as a direct manufacturing tool and as a means of correcting unwanted distortion (perhaps from processes such as chemical etching). To this aim, progress towards repeatable closed loop controlled 3D LF is presented.

II. EXPERIMENT

Initial 3D LF investigations[3] were based around a purely empirical approach to establish rules for the positioning and

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sequencing of the irradiation lines required for the controlled 3D laser forming of symmetrical/uniform saddle and pillow or dome shapes from rectangular $400 \times 200 \times 1.5$ mm mild steel CR4 sheet. It was concluded from this work that the development of an online monitoring system with predictive distortion correction abilities is a requirement if any 3D laser forming operation is to be used in a manufacturing environment. This is due to the unknowns that can be present when forming in an open loop setup, such as residual stresses and variability in the absorption of the incident laser radiation. A foreseeable problem with a system which makes online distortion correction during processing is that the final geometry of the part is not reached until sometime after processing has stopped, when the plate has cooled somewhat and the elastic stresses have been released leaving a plastically formed part.[4] This suggests that a strategy of a one off single pass to produce a required geometry would be extremely difficult to predict and control. A more sensible method of producing a required geometry would be to increment towards it over a number of passes, taking surface measurements after each pass so as to have the ability to take account of any unwanted distortion. The development of a closed loop demonstrator system for 3D laser forming is presented here, based on the recommendations and knowledge gained from empirical 2D and 3D LF studies and through the development of a predictive model.

The experimental study was conducted on 1.5 mm mild steel using a 1.5 kW Electrox CO_2 laser employing a three axis Galil CNC beam delivery system with custom written control software. The mild steel sheet was laser cut into 400×200 mm and 80×80 mm coupons for a 2D and 3D LF study, respectively. The smaller coupons were used to produce calibration data via simple 2D bends for the 3D study on the larger sheets. The bend angles were verified using a laser range finder mounted on the z axis of the system. This was also employed to verify the sheet geometries formed by using control software to setup a coordinate measuring machine (CMM). The samples were held in place on the workbed using a center clamp; this required a hole to be drilled in the center of the plates for a bolt to pass through. Although this may not be a desirable approach (introduction of additional residual stresses), very little forming was induced at the center of the specimen.

III. DEVELOPMENT OF A GEOMETRY BASED MODEL FOR 3D LASER FORMING USING MATLAB

It was concluded from the empirical study[3] that in order to develop control of the process of 3D laser forming it was necessary to have the ability to define the surface to be formed. In addition by defining the surface and analyzing properties such as gradient and curvature, it was thought this may lead to a method of scan strategy prediction. To this aim, a method of surface creation and analysis was devised using Matlab. This study concentrated on the pillow or dome shape, the saddle shape was to be considered once useful results had been found. The key model developments and the results from it are given in the following sections.

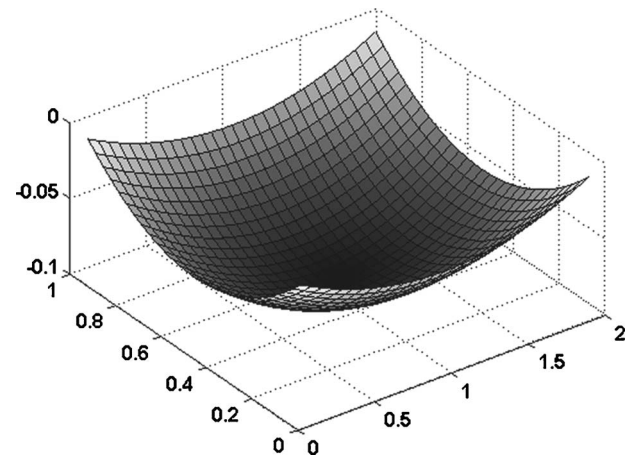

FIG. 1. Matlab output showing a Bezier surface patch for a pillow shape.

A. Initial predictions and results of scan paths for the pillow shape

In order to further understand and control the 3D laser forming process it was considered essential to be able to accurately define and analyze a desired surface. There are a number of methods of defining a surface available [e.g., by equation, $z=fn(x,y)$], one of the more flexible methods is the "Bezier Surface Patch." The Bezier surface patch is the surface extension of the Bezier curve and is widely used in surface definition and graphic rendering for computing applications such as CAD and 3D gaming. Whereas a curve is a function of one variable and takes a sequence of control points, the patch is a function of two variables with an array of control points. Most of the methods for the patch are direct extensions of those for the curves. Bezier patches are defined by a grid of evenly spaced control points that form a surface. These control points (in x, y, and z) can be thought of as specifying the desired shape of the patch; it will attain this shape within the limits imposed by smoothness and continuity. The Bezier patch is generated above the control point grid and interprets the shape of the grid to create a surface that is smooth and continuous. A Bezier patch does not necessarily pass through all of its control points—only the four corner points of the control grid are guaranteed to lie on the surface of the patch, this may not be desirable for control purposes.

As a surface definition using this method involves evaluating a great many polynomials Matlab was used to calculate and display the results. The initial control points were chosen arbitrarily, the dimensions chosen to reflect the 400×200 mm plate size (i.e., 2:1 length to width ratio). The surface definition output from Matlab for the pillow shape can be seen in Fig. 1.

Using this densely populated defined surface (Fig. 1) it was then possible to analyze attributes of the geometry for possible laser forming scan strategy prediction. The first attributes analyzed were the localized gradients in X and Y ($\partial z/\partial x$ and $\partial z/\partial y$, respectively), these were calculated and isolated from the dense surface matrix data. The "gradient" function in Matlab was used to perform this operation. The matrices produced are displayed in the form of contour plots

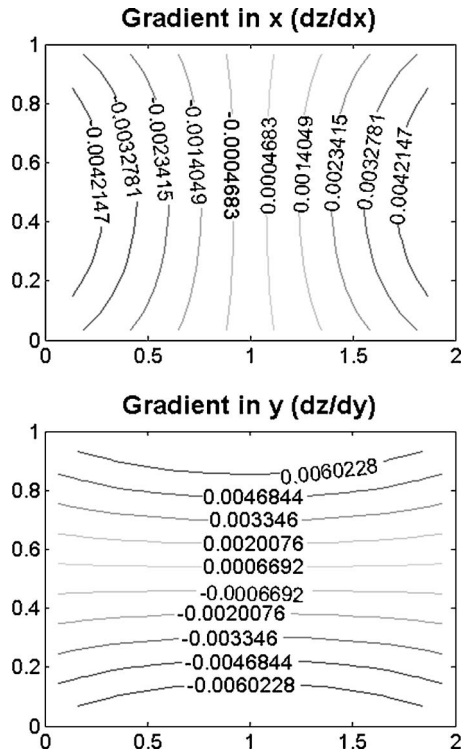

FIG. 2. Contour plots of constant gradient values in X and Y for the pillow shape.

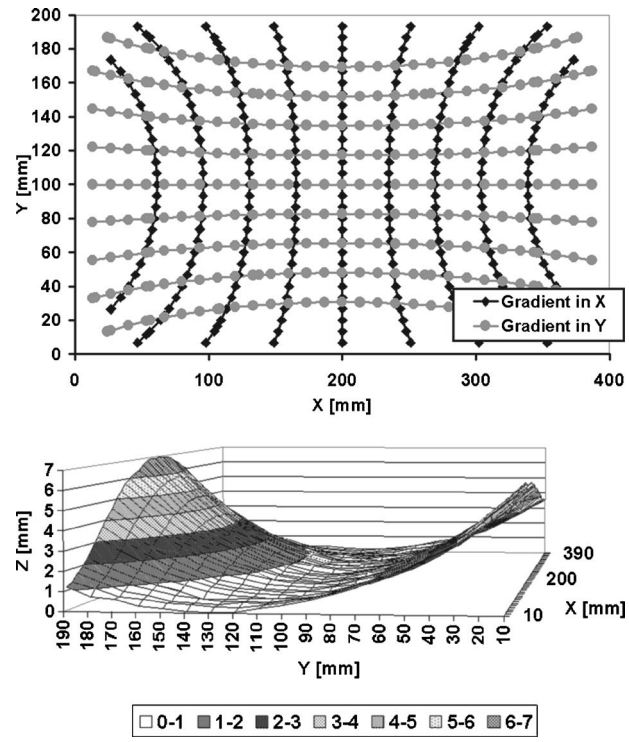

FIG. 3. Matlab data point output of the (overlaid) gradient based scan strategy for the pillow shape and forming results. $\partial z/\partial y$ then $\partial z/\partial x$, alternating directions, 5.5 mm beam diameter, 760 W, and 50 mm/s.

of constant gradient values over the surface in Fig. 2. It was felt that the contour plots in Fig. 2 may indicate a possible scan strategy for the pillow (or dome) shape. If the two contour plots were overlaid and forming (using the temperature gradient mechanism[2] (TGM) due to positive required deformation, in-plane shortening may be necessary as well but this will be discussed later) was realized along the lines of constant gradient values a usable scan strategy may be found. The strategy was tested on the $400\times200\times1.5$ mm mild steel plates using a 5.5 mm beam diameter, 760 W and 50 mm/s traverse speed; these parameters were selected from a 2D LF empirical study on the smaller mild steel coupons and gave a relatively low positive bend angle (discussed later), it was thought that this would avoid distortion due to excessive forming. The scan strategies suggested by Matlab were converted to CNC code by generating a table of x and y points along each contour line (Fig. 3), the Galil controller can then linearly interpolate through these points to produce a smooth irradiation line. The result is also shown in Fig. 3.

A method of combining these gradients was then sought; this was achieved by considering the resultant gradient vector of the data presented in Fig. 3. By combining the $\partial z/\partial x$ and $\partial z/\partial y$ data a resultant gradient vector and magnitude can be found. This was achieved in Matlab using its "quiver" plot capability (Fig. 4). It can be seen in the quiver plot below that the arrow directions and lengths are a representative of the resultant gradient vector and magnitude in X and Y. The density of arrows in the displayed output can be selected in the Matlab program (governed by the x and y grid density for the surface patch).

From the resultant gradient vector quiver plot a second possible scan strategy was observed. By producing contours along values of constant gradient vector angles (or directions) a radial scan pattern emerged (Fig. 4). The scan

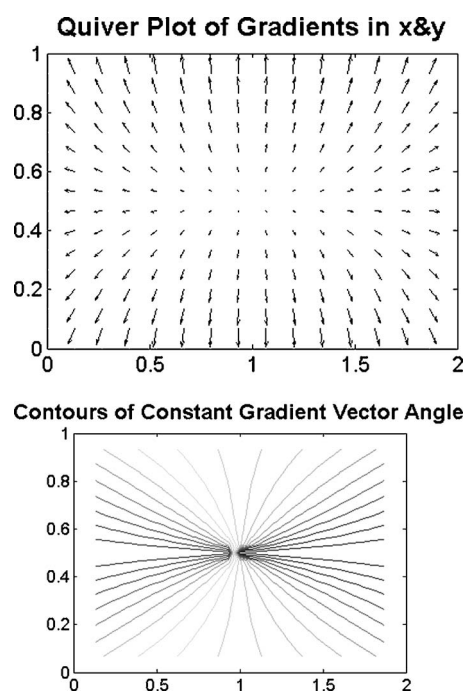

FIG. 4. Quiver plot and contour plot of the resultant gradient vector and magnitude in X and Y for the pillow shape.

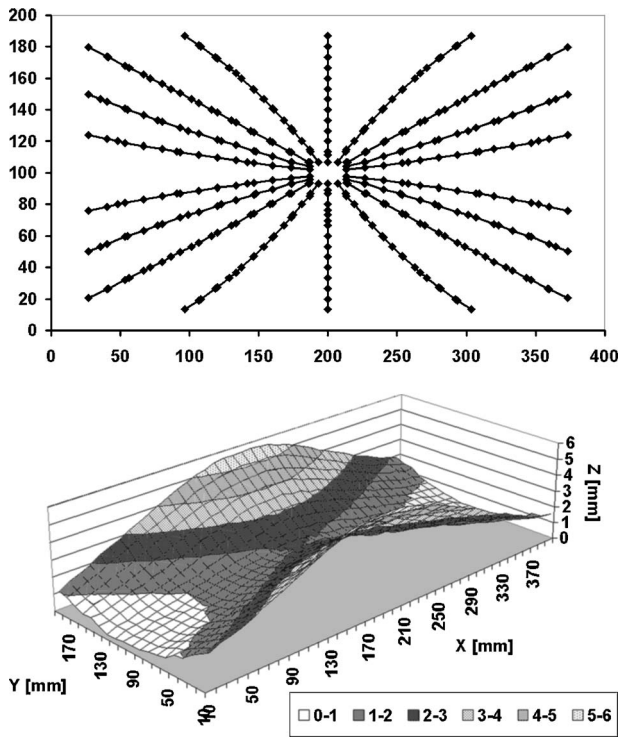

FIG. 5. Constant gradient vector direction based scan strategy for the pillow shape and forming result. 5.5 mm beam diameter, 760 W, and 50 mm/s.

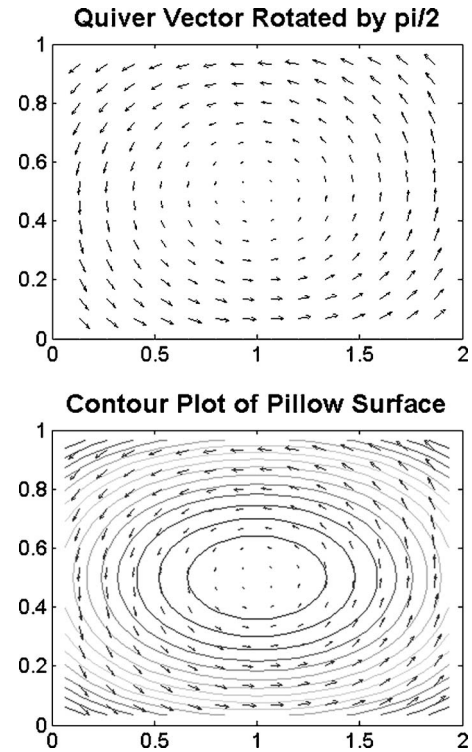

FIG. 7. Quiver plot of resultant gradient vector rotated by 90° for pillow shape.

strategy and the result on a $400\times200\times1.5$ mm mild steel sample can be seen in Fig. 5. The same energy parameters as before were used.

As can be observed in the earlier figure the desired pillow shape has not been formed. A number of variations were also attempted for this strategy such as varying the order and direction of each of the scan lines, however, very similar results to Fig. 5 were produced. It can be seen in this figure that the surface is a reasonably symmetrical saddle shape thus demonstrating yet another method of producing this surface in addition to those already investigated.[3]

By considering the concept of a gradient vector direction in relation to 2D laser forming using the TGM (Ref. 2) it was possible to produce a third scan strategy to investigate. If the resultant gradient vector is in the direction of the bend then in order to laser form a bend in this direction a scan line at 90° to it would have to be realized. This concept is illustrated in Fig. 6. Applying the earlier concept to the resultant gradient vector quiver plot in Fig. 4 involves the rotation of all the gradient vectors by 90° ($\pi/2$). The resultant quiver plot can be seen in Fig. 7.

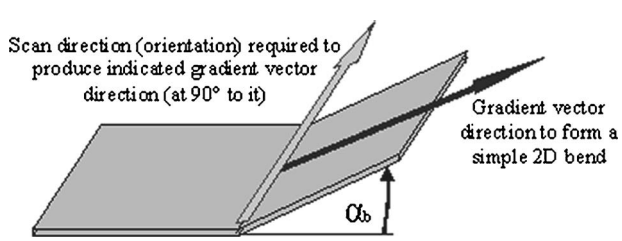

FIG. 6. Illustration of required forming direction for a given gradient vector.

It can be seen in Fig. 7 that a concentric pattern has emerged by rotating the gradient vectors through 90°. On closer inspection it was realized that this concentric pattern corresponds to the contour lines of constant height for the defined pillow surface, this is also shown in Fig. 7 (slight offset observed due to the quiver density and number of contour lines selected).

A test was performed using the contour lines of constant height as a basis for a scan strategy; the results can be seen in Fig. 8. A variable in this method of scan line output was the number of contour levels selected, a limit of nine contour lines was used throughout in order to reduce the amount of manual formatting required to produce the CNC file. The same energy conditions as before were used, namely; 5.5 mm beam diameter, 760 W, and a constant speed of 50 mm/s. The scan line start locations and directions were

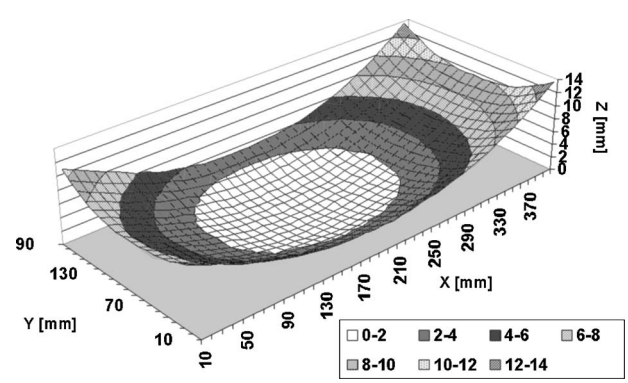

FIG. 8. Contour lines of constant height based strategy forming result. Nine contours, 5.5 mm beam diameter, 760 W, and 50 mm/s.

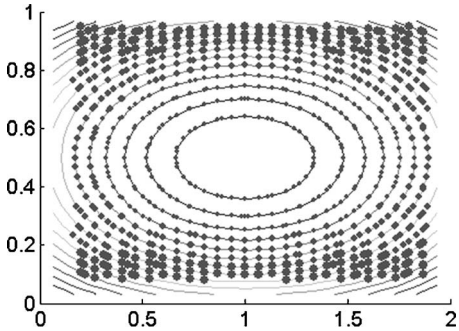

FIG. 9. Height contour plot of pillow surface with an indication of the required gradient vector magnitude at points along the contour lines.

as output from Matlab and so were reasonably random (should aid the reduction of unwanted distortion); the lines were irradiated from the inside to the periphery.

As can be seen in Fig. 8 a smooth contoured reasonably symmetrical pillow shape has been formed using the scan strategy based on lines of constant height of a surface. This could potentially be a relatively straightforward method of predicting a 3D LF scan strategy for a given surface, providing the surface can be defined in the Matlab programming environment.

Although a straightforward solution, this is perhaps not an obvious one. On a continuous nonfaceted surface the contour levels can be arbitrarily chosen (by Matlab in this case) and the localized bend angles along the scan lines are considered small enough so as to not facet the surface significantly. A scan line or a location where a bend takes place about should always correspond to a line of constant height and vice versa since the point about which a moment is generated should be stationary in space and bending legs either side will move instead. The problem does become more complex due to the asymmetric and temporal nature of the process since a scan strategy cannot be realized at all points on a plate instantaneously with the current energy delivery system. Forming one part of the plate will always influence another part (i.e., adding additional stiffness to the geometry), however, providing the scan speed is reasonably high, distortion should be minimized; the result in Fig. 8 indicates this as well.

Now that a usable method of scan line prediction had been discovered it was realized that a more subtle approach to the energy input per scan line was necessary. Observations of the quiver data presented in Fig. 7 indicate that a higher gradient magnitude is required near the edges of the plate as opposed to the center. Hence, increasingly more forming or energy input is required nearer to the edges. This is illustrated further in Fig. 9, where the resultant gradient vector magnitude has been calculated for points along the contour lines of constant height for the pillow shape. The vector magnitude is represented by the size of the blue dot at locations on the lines. It can be noted in Fig. 9 that the gradient vector magnitude not only varies between each contour line but there is also a subtle variation along the same contour line as well. These variations in required gradient vector magnitude should correspond to variations in required energy input and, hence, bend angle or forming requirement to produce the geometry. The most straightforward method of varying the energy input is through the process speed, the Galil CNC controller did have the capability to achieve this along a line of motion, however, the method of speed selection was yet to be determined and will be discussed in the next section.

B. Bending strain and membrane strain requirements for 3D laser forming

It was observed in the previous section that the required energy fluence realized on a sheet during LF will vary depending on the location on a surface. This can be attributed to the fact that for a given surface there will be areas that require more forming than others. A method of determining the distribution of the energy fluence is to simply use the magnitude of the resultant gradient vector as a scaling factor for known energy parameters selected by the traverse speed. Another method is to consider the strain that must be introduced into the material.

From the analysis of thin plates with small deflections[5] (of the order of the plate thickness) the strain components within a sheet can be expressed in terms of the deflection of a plate, w. The strain components at a given location in x and y and the shear strain in the xy plane (for a plate thickness z) during deformation are given by

$$\varepsilon_x = -z\frac{\partial^2 w}{\partial x^2} + \frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2 \tag{1}$$

$$\varepsilon_y = -z\frac{\partial^2 w}{\partial y^2} + \frac{1}{2}\left(\frac{\partial w}{\partial y}\right)^2 \tag{2}$$

$$\gamma_{xy} = \underbrace{-2z\frac{\partial^2 w}{\partial x \partial y}}_{\text{Bending Strain (Small deformation)}} + \underbrace{\frac{\partial w}{\partial x}\frac{\partial w}{\partial y}}_{\text{Membrane Strain (Larger deformation)}} \tag{3}$$

From these equations it can be shown that the membrane strain component is considerably larger than the bending strain required to form a plate where the deformation exceeds the plate thickness. This effectively means that the upsetting or shortening mechanism, rather than the temperature gradient mechanism, is required to introduce large plate deformations. For small plate deformations, the temperature gradient mechanism can be applied. However, an important practical consideration is that the two mechanisms cannot be completely separated.

Liu *et al.*[6] have presented work (building on work by Yu *et al.*[7]) in which the principle of planar development or flattening of a final surface (mathematically) is used to determine the optimized strain field, resolved normal to, e.g., the principle curvature directions, isoparametric lines. The strain field was optimized in the sense that minimum magnitude of membrane strains were introduced, a computationally intense process (many hours for a small

grid of points) that does not always produce a unique solution. This approach would not, therefore, be suitable for iterative laser forming that takes into account the residual stress history of a plate. Resolving the strain perpendicular to, e.g., isoparametric lines, was chosen for mathematical elegance, rather than physical significance: bending strains were not considered in the analysis.

As already mentioned, it is not possible to generate exclusively membrane strains using a laser forming method. A thermal gradient can be present through the thickness even for large diameter beams and low traverse speeds, particularly for materials with low thermal conductivity such as mild steel. If a thermal gradient is present there will be an asymmetry in the plastic strains generated through the thickness, and hence, net bending strains will develop which may cause out of plane deformation depending on the constraints of surrounding material. Similarly for the TGM membrane strains can be developed for larger beam diameter TGM conditions. Forming along lines orthogonal to the principle gradient, i.e., contours of zero gradient or constant height as presented earlier, represent paths that are acceptable for the development of bending strains and membrane strains at the same time. The localized energy input along a contour line (controlled by the scan speed) can therefore be scaled to the bending and membrane strains from the earlier equations, resolved in the direction of the principle gradient.

The scaling factor between known energy parameters and the induced strain can either be found numerically through FEA or empirically by the measurement of the induced deflection for given energy parameters and desired final shape. In addition, if an incremental approach was used to form a surface rather than a single pass implementation, the data obtained from the first pass (providing the final shape has not been achieved) would provide a strain scaling factor for the subsequent passes. This would be based on the current plate being formed and so should take account of residual stress history and material nonuniformity.

The concepts discussed here and the previous sections are implemented in the next section in the development towards controlled 3D laser forming in the form of a demonstrator system based on the nondevelopable pillow shape.

IV. 3D LASER FORMING DEMONSTRATOR SYSTEM

In order to demonstrate the manufacturing capabilities of the 3D laser forming process a 3D LF demonstrator system for the controlled LF of the pillow shape from a $400 \times 200 \times 1.5$ mm mild steel sheet was produced. Systems for controlled 3D LF can either be based on predictive or adaptive approaches. Intelligent predictive systems, perhaps based on knowledge-based systems, neural networks, or thermomechanical models can achieve predictability through a knowledge of the material (including its stress history) combined with a developed, highly tuned process model/control algorithm.

In an adaptive system the use of sensors to provided accurate controlled feedback coupled with the development of intelligent control software, e.g., neural network, provides an incremental or even real time closed loop method of accurate 3D laser forming, based on the current part characteristics independent of material variability, e.g., residual stress.

For the system developed in this work aspects of both approaches were used based on the data presented in the previous sections. A potential method of scan strategy prediction has been developed based on lines of constant height. The energy distribution within the scan strategy can be given either by the gradient vector magnitude or the sum of the bending and membrane strains resolved in the direction of the principle gradient. This gives a potential predictive capability to a system that takes into account material nonuniformity and residual stresses. The system developed here uses the predictive Matlab model to give an initial scan strategy based on a required geometry. When the geometry is not formed within one pass (or over formed), an incremental or iterative adaptive approach can then be used for subsequent passes, utilising the error between the current and desired geometry to give a new scan strategy. Thus any unwanted distortion due to material variability can be accounted for. The forming rate and distribution of the magnitude of forming across the surface can be controlled by the process speed based on the factors above and the amount of forming required so as to avoid overshoot. A strategy of monitoring and controlling the process during a scan was considered, however, this was not possible with the current monitoring hardware. In addition it was observed that the final formed surface was not realised until sometime after forming[8] making online monitoring ineffective. A strategy of per pass monitoring and control was therefore used; a pass being the whole path set for a given iteration. A formed surface was verified using the in-built CMM system; employing a laser range finder to retrieve height data. This system could measure the 400×200 mm samples in approximately 10 min, thus the minimum inter pass delay that could be realized was 10 min also. With improvements to the measurement technique the overall process time could be improved considerably.

A number of developments to the control software, both the Visual Basic based motion control software and the Matlab code, contributed to the development of the demonstrator system presented. A major development was the ability to create the Galil CNC file directly from Matlab. It was realized that Matlab could easily generate the text based file in the correct format (including shutter control commands) thus automating the manual method used so far. This was achieved by creating tables or arrays of x and y locations points (in absolute coordinates) along the predicted contour or scan lines and using the Galil controller's ability to linearly interpolate through these points to create a smooth line of motion. A filter had to be introduced to reduce the number of data points generated in the CNC file as the controller memory was limited to 1000 lines of code. This was not detrimental to the smoothness or accuracy of motion as data points as far apart as 10 mm could be linearly interpolated between successfully. Another important development was the ability to vary the scan speed, not only for each contour line but dynamically along each contour as well. This exploits the Gallil controller's ability to accept for every x and

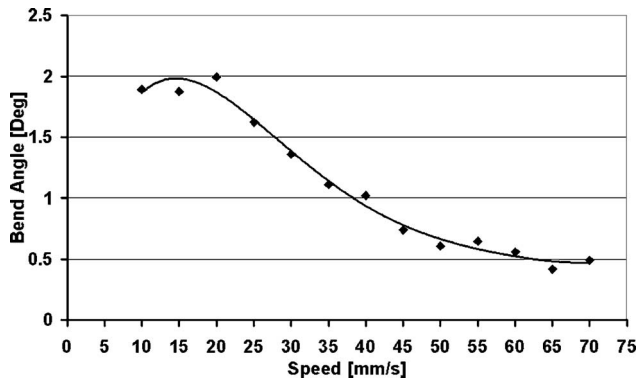

FIG. 10. Laser forming of 1.5 mm mild steel, 5.5 mm beam diam, 760 W, 10–70 mm/s calibration data.

y location data point (used for linear interpolation) a starting and end speed between each point. This dynamic control of the process speed allows for the implementation of a variable energy distribution (controlled by the speed) scaled dependent on either the gradient vector magnitude or total strain requirements.

Regions that become overformed are indicated by red scan lines and were ignored by the subroutine for CNC file generation. Our preferred strategy is to avoid overforming, as it may well require backsurface forming to rectify.

A change to how the desired surface was described was also implemented. The Bezier surface route, although extremely flexible, does not guarantee the defined surface passes through the specified control points (due to constraints on the smoothness of the surface produced). As a demonstration of the potential accuracy of the process was the intention of the system, a more accurate surface definition was used. The pillow shape falls into the mathematical surface category of an "elliptic paraboloid" similarly the saddle shape is a "hyperbolic paraboloid." Both these surfaces can be described by a mathematical equation. As stated, the speed distribution over the plate based on the sum of the bending and membrane strains resolved in the direction of the principle gradient. The initial speed distribution was taken from the calibration data available from a 2D empirical study on 80×80 mm coupons using a 5.5 mm beam diameter and 760 W (Fig. 10). For a given speed an induced bend angle is known. After pass 1 a calibration was made between the predicted deformation and the actual deformation to ascertain an approximate strain scaling factor for subsequent passes. This takes account of the fact that the 2D LF data are taken from a single bend location from edge to edge, and that the same energy parameters would not necessarily produce the same amount of forming in the center of a plate due to the additional stiffness and constraints.

In order to avoid overshoot the minimum process speed (selected initially by the user) was monitored and varied according to the magnitude of the error between the current and desired surfaces, such that as the desired deformation approached the minimum speed distributed over the plate per pass would increase and the forming rate would decrease. This technique has proved extremely useful for closed loop 2D LF.[9]

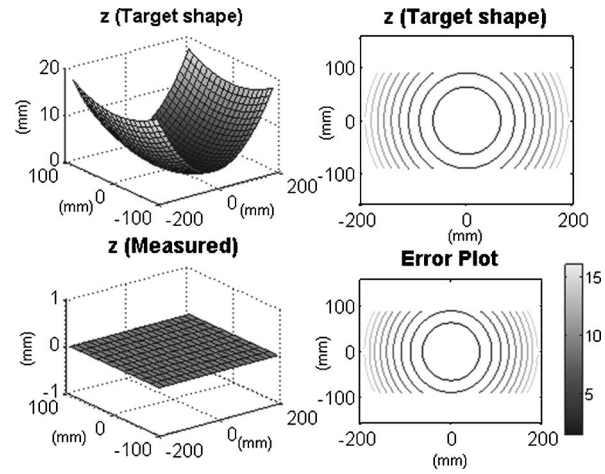

FIG. 11. Desired 20 mm max deflection pillow shape and error plot between it and the flat unformed sheet.

A forming sequence from the 3D LF demonstrator system is given in Figs. 11–19, based on the forming of a pillow shape (equation based) with a 20 mm maximum deflection. 760 W, 5.5 mm beam diameter, and 50–85 mm/s are used. A predicted scan strategy for the first pass is shown in Fig. 12; the speed distribution realised on the plate surface is indicated by the size of the dots along a given scan line, the larger the dot the higher the speed. The lines were irradiated from the inside (the point of smallest required displacement)

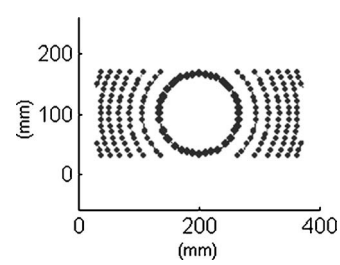

FIG. 12. Predicted scan strategy and speed distribution for pass 1. Speed range 50–85 mm/s. (indicated by the size of the dots along the scan lines).

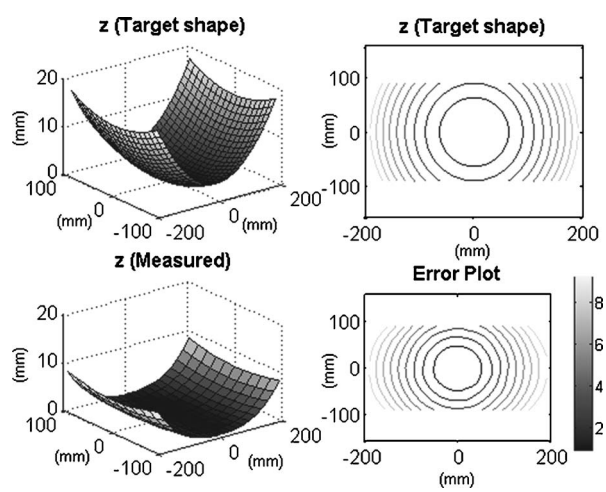

FIG. 13. Comparison between formed surface after pass 1 and desired shape, ~12 mm difference. Error plot gives a prediction for the next pass.

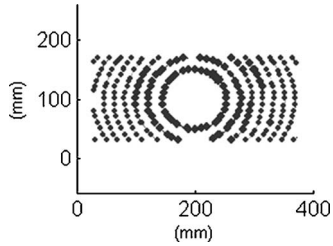

FIG. 14. Predicted scan strategy and speed distribution for pass 2. Speed range now 67–85 mm/s so as to avoid overshoot.

to the periphery, using an alternating direction and start location so as to achieve an even heat distribution.

V. DISCUSSION AND CONCLUSIONS

The laser forming sequence shown in Figs. 11–19 demonstrates the potential for closed loop repeatable 3D LF of continuous surfaces. Using an iterative approach based on the error between the current and desired surfaces it has been possible to produce a component to within ±2.5 mm of the target shape. LF using scan patterns based initially on contours of constant height and then error difference plots have been shown to produce useful results.

Providing overforming has not occurred on the first pass it has been possible to iterate towards the final shape increasing the traverse speed to reduce the bend angle rate and calibrating for the current plate's forming characteristics. It has the potential to produce a final component independent of residual stress history and material nonuniformity and take account of unwanted distortion, perhaps brought about by these two factors or process variability.

The energy distribution based on the sum of the bending and membrane strains resolved in the direction of the principle gradient has been shown to be of merit. However, the differences between this method and trials using the gradient vector magnitude distribution are subtle as the possible speed range is limited to between the manually selected minimum

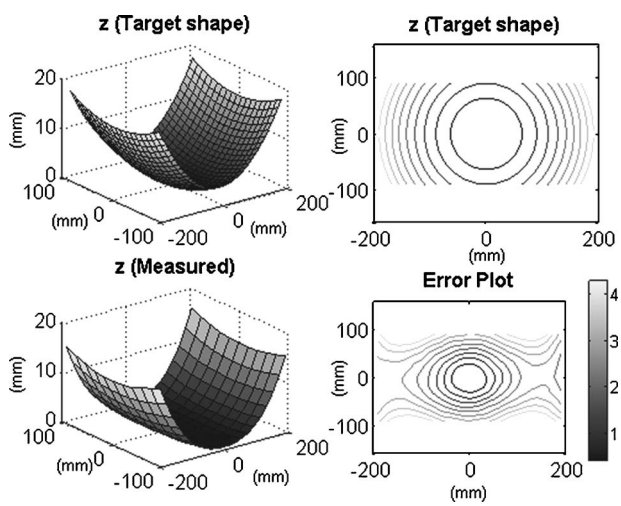

FIG. 15. Comparison between formed surface after pass 2 and desired shape, ~4.5 mm difference. Error plot gives a prediction for the next pass.

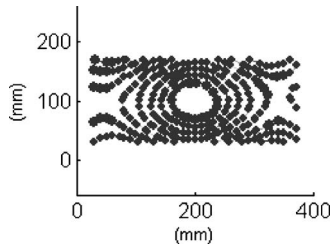

FIG. 16. Predicted scan strategy and speed distribution for pass 3. Speed range now 73–85 mm/s. A more complex scan pattern now required for small corrections.

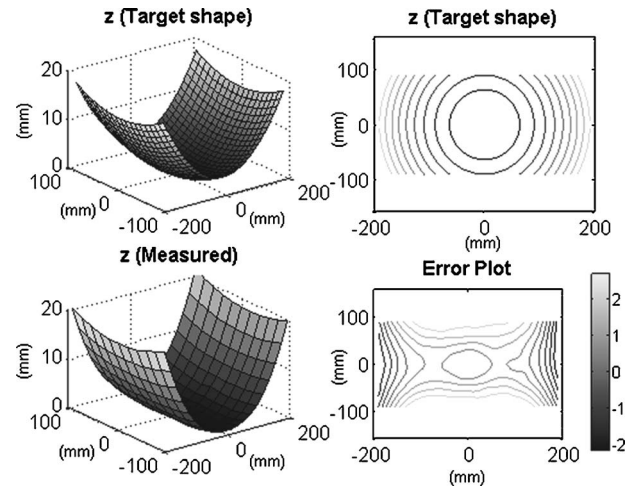

FIG. 17. Comparison between formed surface after pass 3 and desired shape, ±2.5 mm error.

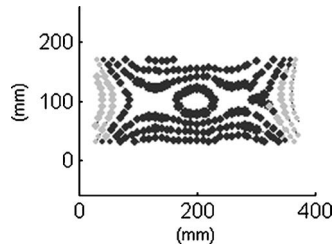

FIG. 18. Predicted scan strategy for pass 4 suggests forming on the reverse side of the plate (light coloured dots) to account for the slight overshoot.

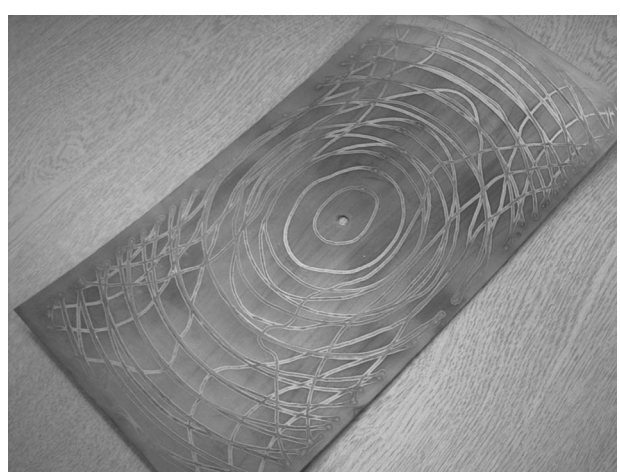

FIG. 19. Image of a laser formed 400×200×1.5 mm mild steel plate showing the complex scan patterns realized over the surface.

speed, and the maximum speed where no forming occurs (inferred from the 2D laser forming empirical data). These similarities are accounted for by the approximate in-process calibration after pass 1, which is required because no accurate membrane calibration data were available. Further work has been undertaken to calibrate the membrane strains and to combine bending and membrane strains into a general iterative forming strategy.[10]

A number of limitations of the demonstrator system have been identified from the process trials on the pillow shape. First, it is currently possible to overshoot the target shape by a small degree. Refinements to how the speed is scaled as the target shape is approached may avert this problem. On reflection it may be beneficial to overform to some degree to reduce the error near the center of the plate and then turn the plate over to bend the outer edges back to the required deformation. This highlights another limitation of the system as no account is taken of the influence on the rest of the plate of each forming line. The forming lines at the center of the plate will cause a deflection of the outer edges and so the amount of forming required near the edges must reduce. This stems from the use of the large beam diameter TGM conditions (bending strain) and the assumption that a significant amount of in-plane strain is still present. It may be the case that there is a limit to the amount of (required) distortion that can be produced in a nondevelopable surface using these hybrid TGM conditions. If a large amount of distortion is required in say a dome or pillow shape then a shortening regime (large beam and low traverse speed) may be required to account for the additional material preventing the formation of the desired shape. A combination between the two mechanisms may in fact be necessary, the TGM for accurate shape definition and the shortening mechanism to selectively account for the additional material. The system as it stands, however, should be ideally suited to the laser forming of developable surfaces such as a part cylinder and possibly a twisted blade shape; this should be shown by further research.

The system presented does demonstrate the potential of the laser forming process to produce accurate repeatable 3D surfaces in a controlled way. This suggests that laser forming could be utilized as a direct manufacturing tool or as a means of distortion removal in an industrial environment. Providing the desired and the current surfaces can be realised in a virtual way (e.g., CMM data with a Bezier surface patch), a scan strategy can be predicted to give the final shape. Ongoing improvements to the Matlab code will hopefully lead to a full realization of this concept. Further work recommended on this system includes investigations into the use of other materials of different dimensions and forming of nonsymmetrical shapes and irregular shapes (nonrectangular) so as to ascertain the robustness of this 3D laser forming method.

ACKNOWLEDGMENTS

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[1]J. Magee, K. G. Watkins, and W. M. Steen, "Advances in Laser Forming," J. Laser Appl. **10**, 235–246 (1998).

[2]F. Vollertsen, "Forming, Sintering and Rapid Prototyping," in *Handbook of the Eurolaser Academy*, edited by D. Schuöker (Chapman & Hall, London, 1998), pp. 357–453.

[3]S. P. Edwardson, K. G. Watkins, G. Dearden, and J. Magee, "Generation of 3D Shapes Using a Laser Forming Technique," Proceedings of ICALEO'2001, Jacksonville, FL, 2–5 October 2001, Sec. D.

[4]S. P. Edwardson, K. G. Watkins, G. Dearden, P. French, and J. Magee, "Strain Gauge Analysis of Laser Forming," J. Laser Appl. **15**, 225–232 (2004).

[5]D. McFarland, B. L. Smith, and W. D. Bernhart, *Analysis of Plates* (Spartan, New York, 1972).

[6]C. Liu, Y. L. Yao, and V. Srinivasan, "Optimal Process Planning for Laser Forming of Doubly Curved Shapes," Proceedings of ICALEO'2002, Scottsdale, AZ, 14–17 October 2002.

[7]G. Yu, N. M. Patrikalakis, and T. Maekawa, "Optimal Development of Doubly Curved Surfaces," Comput. Aided Geom. Des. **17**, 545–577 (2000).

[8]M. Reeves *et al.*, "Dynamic Distortion Measurements during Laser Forming of Ti-6Al-4V and their Comparison with a Finite Element Model," Proc. Inst. Mech. Eng. Part B: J. Eng. Manuf. **217**, 1685–1696 (2003).

[9]J. Kim and S. Na, "A Study on the Laser Forming for Free Curve Generation," Proceedings of ICALEO'2003, Paper 104, Jacksonville, FL, 13–16 October 2003.

[10]R. McBride, A. J. Moore, D. P. Hand, and J. D. C. Jones, "Calibration of Bending and Membrane Strains for Iterative Laser Forming of Non-Developable Surfaces," Proceedings of ICALEO'2004, San Francisco, CA, 4–7 October 2004.