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Geometrical technique for closed loop 3-dimensional laser forming

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Abstract. Laser forming is a non-contact thermal forming process that can shape metallic components as a means of rapid prototyping and as a method of distortion correction, adjusting and alignment. The process utilises a defocused laser beam to introduce thermal stresses, without melting, that cause plastic deformation resulting in controlled deformation. To advance this process further for realistic forming applications in a manufacturing industry, it is necessary to consider controlled 3D laser forming. The work presented in this paper uses a predictive and adaptive approach to control the 3D laser forming of aluminium alloy 5251. Key to the control of the process has been the development of a predictive Matlab based model. This model calculates scan strategies derived from the required geometry. Scan lines are determined using lines of constant angle and traverse speed by considering the change in angle between these lines. The rate of forming and distribution of the magnitude of forming across the surface are controlled by the number of scan lines. When the geometry is not formed within one pass, an incremental adaptive approach is used for subsequent passes, utilising the error between the current and desired geometry to give a new scan strategy, By this means, any unwanted distortion due to material variability can be accounted for. Results are presented that demonstrate the controlled laser forming of a 3D semi-developable shape in an accurate and repeatable way on both large and small scale components. The data presented represents a significant step towards a realistic laser forming system for the manufacturing environment.

1. Introduction

The inspiration behind Laser Forming (LF) originates in the flame bending or “line-heating” process. Flame bending uses an oxy-acetylene torch as a heat source and has been used extensively for the curving and straightening of heavy engineering components. However an oxy-acetylene torch lacks the subtleties of a laser. With minimal heating to surrounding material the use of a laser makes it easier to regulate energy absorption in localised areas. This allows for much greater control in the forming of a work-piece. Combine this with CNC control and the possibilities of an automated forming process become apparent.

LF has become viable for the shaping of metallic components, as a means of rapid prototyping and for adjusting and aligning. LF 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 work-piece 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 split into two groups, basic single line 2D forming that produces shapes that are folds of varying angles, and more complicated multi-line 3D forming that produces continuous surfaces. 3D forming compromises ‘developable forming’, which is a series of 2D bends producing a surface with a single curvature and ‘non-developable forming’ which makes use of the shortening mechanism to produce a surface containing a double curvature.

To advance the LF process for realistic forming applications and for straightening and aligning operations in a manufacturing environment, it is necessary to consider controlled 3D LF. In order to compete directly with conventional forming techniques, 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 benefit. A change to required part geometry could be implemented easily through the CAD driven process, which 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. To this aim, progress towards repeatable closed loop controlled 3D LF is presented.

2. Experimental

Initial 3D LF investigations [3] were based around a purely empirical approach to establish rules for the positioning and sequencing of the irradiation lines required for the controlled 3D laser forming of symmetrical/uniform saddle and pillow (‘dome’) shapes from rectangular 400x200x1.5mm mild steel CR4 sheet. It was concluded from this work that the development of an on-line 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 set-up, 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 errors due to unwanted distortion. With the forming of saddle, pillow shapes and any non-developable shape the magnitude of forming is limited when using the Temperature Gradient Mechanism (TGM) as it is principally an out of plane forming mechanism, where non-developable shapes need an in plane, or shortening, mechanism [5]. Because of the added complexity in forming non-developable parts, it is easier to consider a largely developable shape, with some slightly non-developable areas. In previous studies [5, 6] lines of constant height were used to calculate the irradiation path. For this investigation lines of constant angle are used. Because the shape is mostly developable and is therefore a series of 2D bends the idea behind lines of constant angle is very simple.

In 2D LF, when using the TGM to achieve a bend, a line is scanned at a right angle to the direction of the bend (figure 1).

This method treats each segment as an individual 2D bend and simply connects the angles that are equal. The contours are spread in equal increments of angle (figure 2). The angle increment between each contour is then used to calculate the speed of the scan lines.

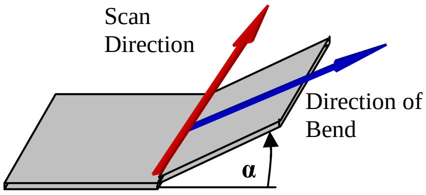

Figure 1 Schematic of a two dimensional bend.

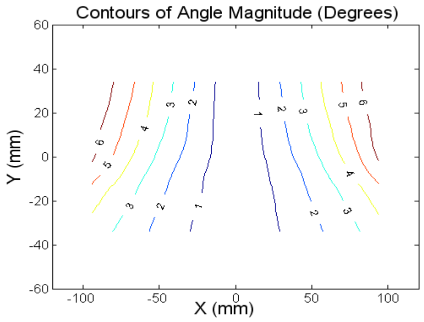

Figure 2 Distribution of (LF) irradiation lines.

Speed here is used to control the energy input, which is one of the main influencing parameters of bend angle [2]. The speed is calculated from 2D investigation where a series of 2D bends were formed at various speeds producing the graph in figure 3. This method forms the part evenly and reduces the possibility of over forming at the edges which is a drawback with using contours of constant height [5, 6].It was concluded from earlier empirical studies [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. The desired shape (based on a form of aircraft cowling) may be defined by a Bezier surface patch (figure 4) in Matlab.

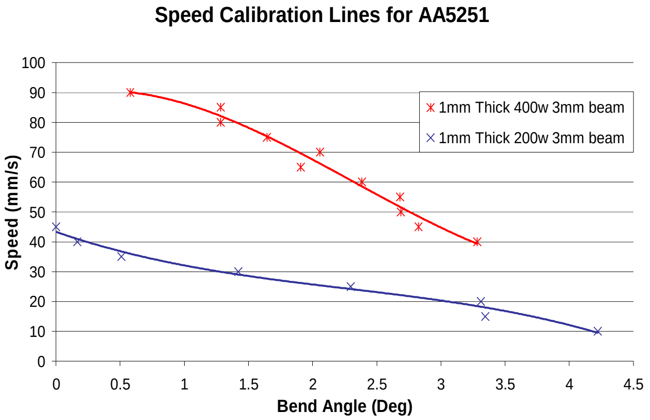

Figure 3 Speed calibration graph.

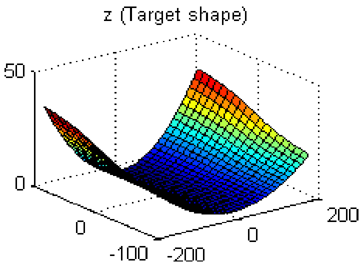

Figure 4 Interpolated points defining desired shape.

This mathematical function allows the definition of a continuous 3D surface from only a limited number of supplied coordinates for the surface (e.g. 16), the rest of the data then being interpolated over a given range.

In addition it was realised that as the scan strategy prediction is geometry based the error between a given shape and a desired shape could form the basis for a further scan strategy. Contours of error between two surfaces are akin to the error between a flat sheet and a desired shape that give the contours of angle. This can allow for the correction of a formed shape if the desired shape is not formed by the initial prediction. Thus an iterative method can be used to increment towards a desired shape. This method also allows for the correction of unwanted distortion in a pre-formed shape, by forming on both sides of a component.

The experimental study was conducted on LF of graphite-coated 1mm thick AA 5251 using a 1.5kW Electrox CW CO_2 laser with a 3-axis Galil CNC beam delivery system with custom written control software. The aluminium was cut into 400x200mm and 100x80mm coupons a 3D LF study and 80x80mm coupons for a 2D LF study. The coupons were used to produce calibration data via simple 2D bends for the 3D study. A diode laser range finder, mounted on the z-axis of the LF system, was used to verify/measure the bend angles in 2D LF and also the surface shape in 3D LF, by using control software to create a co-ordinate measuring machine (CMM) set-up. The samples were held in place on the workstation table using a centre clamp; this required a hole to be drilled in the centre of the plates for a bolt to pass through.

3. Results and Discussion

Using an iterative approach based on the error between the current and desired surfaces it was possible to produce a component to within -5mm and +3mm maximum error in 200x80mm AA 5251 at 400W. This demonstrated both accurate 3D LF and a means of distortion correction as the system can create a new strategy based on the current shape (figure 5). However, this produces a heavily faceted piece with dwell marks, where the

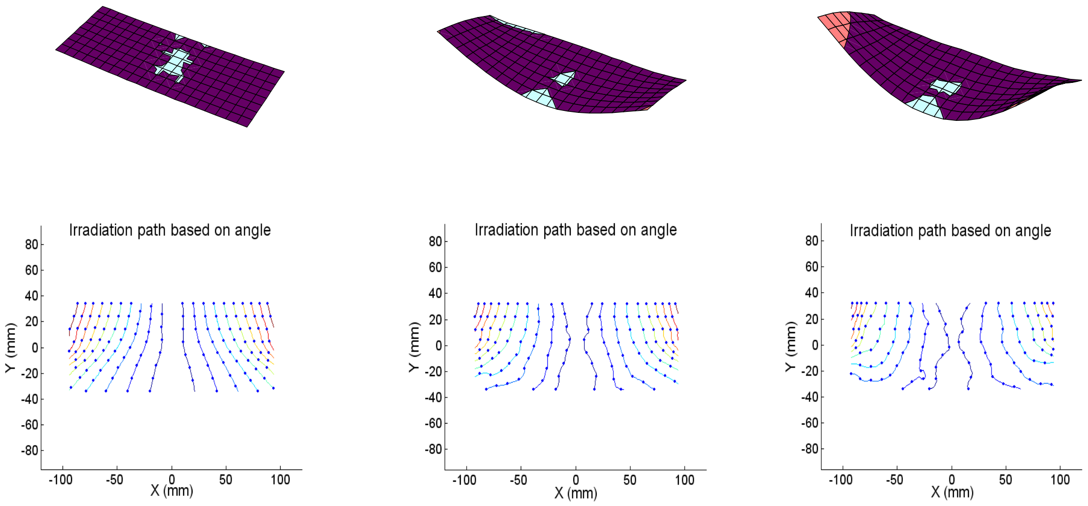

Figure 5 Surface measurement and subsequent LF scans for first 3 passes of 200x80mm AA5251.

material has melted (figure 6). To prevent further faceting and melting the power was reduced to 200W and the speeds were decreased to achieve the same amount of forming (figure 3).This produced a component to within +/- 5mm. This produced a part with very little visible surface effects (figure 7). When scaled up to 400x200mm there was a great deal more forming than expected with the first pass producing an over formed part with an error of -2mm and +12mm (figure 8).This can easily be improved with a reduction in speed. Another reason for over forming was that the part moves into focus as it is formed, which reduced the spot size and increased the fluence on the outer paths. A solution to this would be to start the scan path at the outside and working inwards, the laser then passes over sections that have not yet moved. This will reduce the increase in forming due too moving into focus.

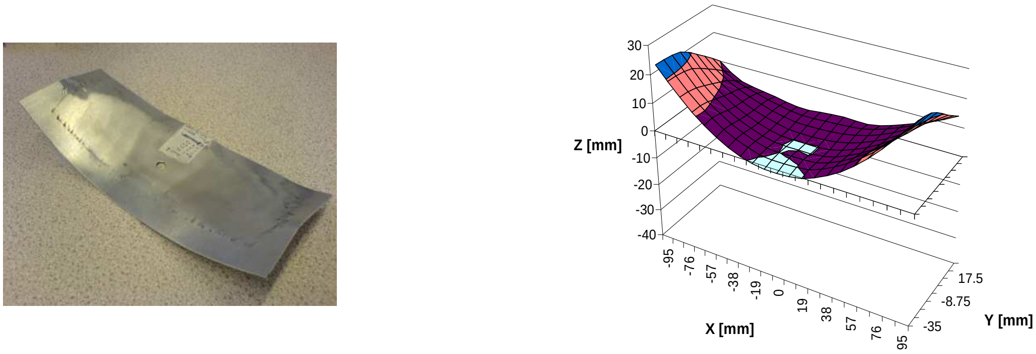

Figure 6 Final shape of 200x80mm AA5251 component (400W laser power).

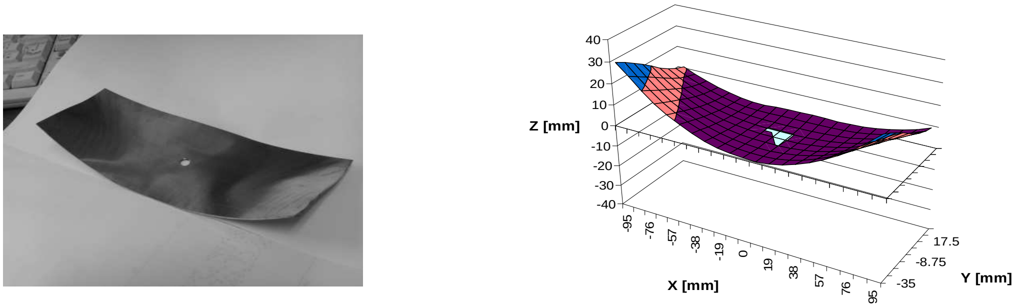

Figure 7 Final shape of 200x80mm AA5251 component (200W laser power).

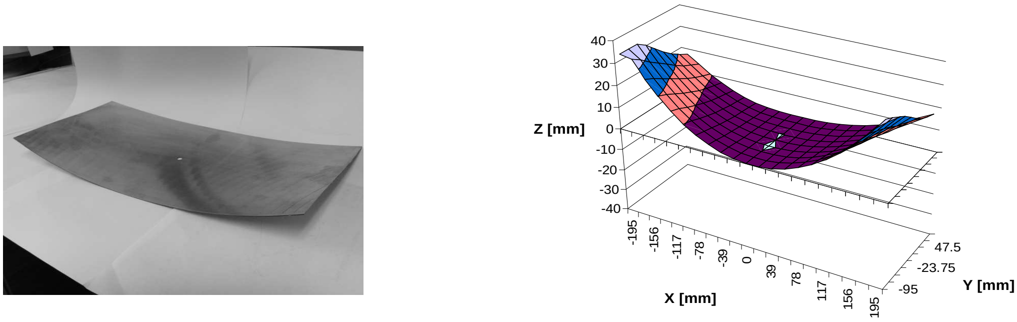

Figure 8 Final shape of 400x200mm AA5251 component (200W laser power).

4. Conclusions

- It is possible to predict an irradiation strategy for developable shapes using contours of angle.
- By using an iterative pass-by-pass approach, it has been possible to form a 3D shape in a controlled manner to a reasonable degree of accuracy, taking account of unwanted deformations from program error or material non-uniformity
- The system can be used for correction distortion with the ability to calculate a scan strategy to form a shape from just about any other shape
- Size or ratio of a part effects how it reacts to laser forming, further 2D investigation is need to be able to increase the accuracy of the system
- Further investigation into speed calibration is needed
- Although the system is very good at creating accurate shapes, for smaller adjustments more investigation is needed.

5. References

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