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Parametric Studies of Vacuum Assisted Laser Forming

Author, Janakkumar R Tanna
K. J. Institute of Engineering & Technology/Affiliated with GTU, Savli Gujarat, India- 391770
Email: janak.tanna@kjit.org, janak.svkd@yahoo.co.in

Abstract— Laser forming of sheet metal offers the advantages of requiring no hard tooling and thus reduced cost and increased flexibility. It also enables forming of some materials and shapes that are not possible now. In single-axis laser bending of sheet, the bending edge is found to be somewhat curved and the bending angle varies along the laser-scanning path. These phenomena are termed edge effects, which adversely affect the accuracy of the bending and result in stress. Numerical investigations are carried out to study the process transiency and the mechanism of the edge effects. Temperature dependency of material properties and strain-rate dependency of low stress are considered in the numerical simulation to improve prediction accuracy. Numerical results are validated in experiments. Patterns of edge effects and resultant stress distributions are examined under a wide range of conditions. Experiment set up for vacuum assisted laser forming has been also developed. FE analysis includes a static coupled thermal-structural analysis accounting for the temperature dependency of the thermal and mechanical properties of the material. The time dependent temperature and bending angle have been obtained from the simulation. (Material property of AISI 1010 and pure aluminum is used in FE model and experiments). Three dimensional FE-simulations model has been developed with the help of ANSYS software.

Key Words— Vacuum assisted laser forming; Thermal-structural coupled Analysis, Micro-cup.

1 INTRODUCTION

LASER forming is a newly developed technique for the shaping of metallic components. The process is achieved by introducing thermal stresses into a sheet of metal by controlled irradiation with a defocused laser beam. In laser forming, the shape and position of a bend are determined by the intensity, scanning speed, beam size and positioning of the laser which are process variables that can be changed or adjusted through electronic control. In conventional forming techniques such as bending, drawing, pressing and stamping special heavy tools (i.e., die and punch), and application of external forces are required to bend at sheet metal into a component, where the process is changed through re-tooling or rebuilding the forming machines (Fig 1). Thus, the greatest advantage of the laser forming technique over the conventional methods for small batch production can be placed on process flexibility and reduction of manufacturing cost and time. Promising potential application of laser forming to micro-scale forming arise in rapid prototyping and shape correction in automotive, aerospace, and shipbuilding sectors. Micro-scale laser forming for precision adjustment of-components in the microelectronics industries is another application, and several laser micro-adjustment techniques are currently under development [1] [2]. A vacuum assisted laser forming has been proposed for micro forming of metal components. A cup-shaped micro component has been formed from circular sheet with vacuum assisted laser forming.

2.1 Working Principle of Laser Forming

‘Thermal stress are introducing into the surface of work piece with high power laser beam. These internal stresses induced plastic strain that bend the material or resultt in elastic-plastic buckling’. In laser forming heat is applied on the surface of the work piece with high power laser beam. So, by application of heat temperature gradient is generated across the thickness of work piece and produce thermal stress across the thickness. These internal stresses induced plastic strain that bend the material or result in elastic-plastic buckling and bend the sheet. Figure 1.3 illustrates the schematic diagram of a straight-line irradiation process which produces a bend angle from a at sheet metal piece. The sheet metal is clamped at one side on a CNC (Computer Numerical Control) machine. The heating on the material surface by a laser beam occurs on one side along a selected line while the CNC table is moving. The surface melting of the material is avoided by adjusting the laser parameters such as laser power, feed rate and beam diameter. The sheet metal expands in the heated zone and thermal stresses are produced by the restriction of the surrounding material. The thermal stresses lead to a bend angle in the sheet metal. The principle of the thermal deformation is described in detail in the following section [2].

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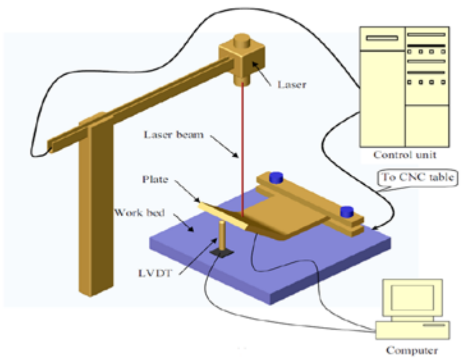

Fig 1: Schematic view of a straight-line irradiation by a focused laser beam to produce bend angle from a flat sheet metal.

2.2 Mechanism of Laser Forming Process

There are three key mechanisms which are used to determine the laser forming process.

- TGM -Temperature gradient mechanism
- BM -Buckling mechanism
- UM-Upsetting mechanism

Temperature gradient mechanism:

TGM can be used to bend sheet material out of plane towards the beam. Figure 2.1 shows the temperature gradient mechanism involved in the laser forming process. The condition for TGM are laser beam diameter is lesser than plate thickness and laser beam of high power density is rapidly guided across the surface of a metal sheet, so the laser beam forms steep temperature gradient across the thickness direction of metal sheet as shown in Figure 2.1(a).As a result, a differential thermal expansion occurs through the thickness direction. Initially, the material expands in the heated zone so that the whole shape of the material bends away from the beam as shown in Figure 2.1(b). This is called 'counter-bending'. This thermal expansion is converted into elastic tensile strain and compressive stress because free expansion of the heated material is restricted by surrounding material. Once the stress reaches the temperature-gradient stress, any additional thermal expansion is converted into a plastic strain. So, plastic compressive deformation occurs near the top surface because of restriction of surrounding material. But compressive force does not occur at the bottom surface as temperature is low. During cooling periods the material in top layer contracts and then local shorting of this layer makes the plate bend towards the beam as shown in figure [4].

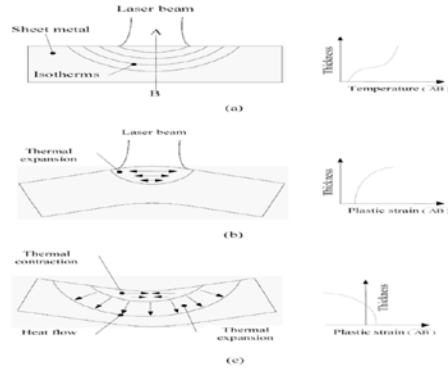

Fig 2.1: Temperature gradient mechanism involved in the laser forming process: (a) Temperature gradient (b) during heating; and (c) During cooling

Buckling Mechanism:

BM can be used to bend sheet material out of plane away from the beam or towards the beam. Figure 2.2 shows the buckling mechanism involved in the laser forming process. Compared to the TGM, the BM can be generated by reducing the feed rate and increasing the beam diameter in order to avoid the steep temperature gradient involved in the TGM. Unlike the TGM, The bending direction is not changing during the heating and cooling process. The bending direction in BM is depends on (a) pre-bending orientation of sheet; (b) internal stresses; (3) external or gravitational forces. It is possible to bend sheet in any direction so BM gives advantage of flexible manufacturing process. Figure 2.2(a) shows the compressive thermal stress generated by the laser beam. It can be seen that no temperature gradient in sheet metal. Figure 2.2(b) shows the starting of buckling developed in metal sheet. As discuss above buckle can be towards or away from beam. Figure 2.2(c) presents the plastic and elastic deformation in sheet metal. Plastic buckling occurs at top of metal sheet because yield stress is low. In this region due to temperature rise and elastics buckling occur at neighbouring region of plastic buckling due to lower temperature. Buckling increases along the scanning line. Figure2.2 (d) shows the full development of bend angle. Buckle is generated in whole sheet when beam is leave from sheet.

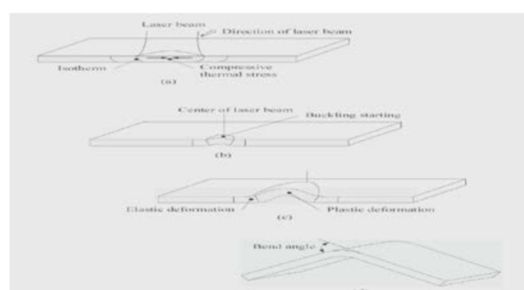

Fig 2.2: Laser forming stages by BM:
(a) Generation of thermal compressive stresses by a laser beam; (b) Development of buckling by thermal stresses; (c) Development of elastic and plastic deformations; and (d) Development of a bend angle

Upsetting or Shorting:

UM can be used to shorten or upset a work piece in a plane. Figure 2.3 shows the upsetting mechanism involved in the laser forming process. The upsetting mechanism is shortening mechanism. In this mechanism thickness is higher than the beam diameter and sheet is kept thicker and stiffer to avoid buckling. In UM process sheet metal is continuously expanded through thickness direction during heating and it contracts in with during cooling. Thus in UM the thickness of plate increases.

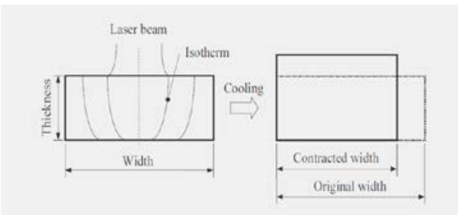

Fig 2.3: Laser forming by the UM

During the laser forming process, a metal plate is clamped at one side. As shown in Fig. 1, a scanner moves along the x-axis with a constant laser power and scanning speed, and the metal plate is cooled by ambient air after the laser beam passes.Fig.2.4(a) shows the forming process under the conditions of the upsetting mechanism. The temperature difference along the thickness direction is smaller when as lowers canning speed and a larger laser spot diameter are adopted. The process parameters are similar to those of the BM, but for this mechanism the geometry of the plate prevents buckling due to an increased moment of inertia. In the scanning process, the material in the heated area is compressed by restriction of thermal expansion from the surrounding cool material as the temperature rises and flow stress slower. The compression plastic strain difference between the top surface and the bottom surface is also reduced. During cooling, the material contracts but the plastic deformation cannot recover. This results in a shortening of material of the heated area and a thickness increase in the heated region. On the other hand, a small bending deformation towards the laser beam also occurs because the compression plastic strain of the top surface is somewhat greater than that of the bottom surface, as shown in Fig. 2.4(b) [5].

2.3 ANALYTICAL MODEL

The analytical models were used to identify relationships between the bend angle and the process parameters (i.e., forming mechanisms). At present, it is not clear how many mechanisms exist in the laser forming. In general, three mechanisms are suggested by many researchers: temperature gradient mechanism (TGM); buckling mechanism (BM); and upsetting mechanism (UM) [5]. An analytical model for the TGM proposed by Vollertsen [2] is described in this section. The TGM may be used to bend thick plates towards the laser beam source. An analytical model for the TGM proposed by Vollertsen [2] is described in this section. For his model, he used a pure energy approach, made for flame bending, which is based on the assumption that the power transferred to the sheet metal is converted into a bending action similar to that which would be produced by mechanical bending using the same power. However, the bend angle from the energy approach yielded very high angle which is some orders of magnitude above the measured one [5]. In the model, it is assumed that the thermal expansion is fully restricted, thus it is fully converted into plastic compression. The temperature increase of the heated layer is calculated as follows:

$$a=3lhath4\Delta T/2s0 \qquad (2.1)$$

Where: A= Laser power absorption co-efficient; P = Laser beam power; V = Feed rate; cp= Heat capacity; *lh*= Length heated; s0 = Plate thickness; αth= Coefficient of thermal expansion; α = Bend angle; He assumed that the thermal expansion of the upper layer is fully converted into plastic compressive strain. The plastic strain is given from the co-efficient of thermal expansion and the temperature increase of Eq. (2.1).
The bend angle after cooling is

$$\Delta T =2AP/VCplhs0 \qquad (2.2)$$

2.4 Finite Element Modelling

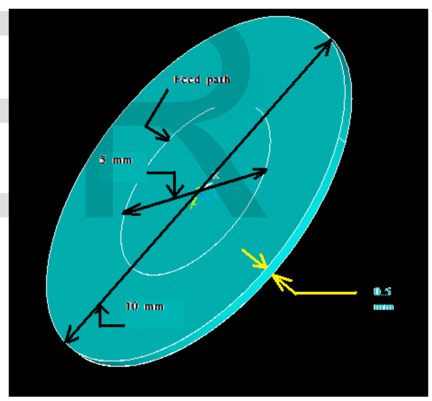

Fig 2.4: A circular blank of 10mm diameter has been modelled using pre-processor of ANSYS software

The heat losses are largely governed by conduction into surrounding material for the duration operation and small amount of heat is lost by natural convection and radiation from plate surface. The sheet has thickness from 0.1 mm to 0.5 mm. Beam varies from 0.1 to 0.5 mm and the vacuum taken is 0.1 to 0.5 N/mm2.

Calculation for Bending Angle:
From FE analysis deformation results are shown in ANSYS. Bending angle will be calculated as below:
tanα=1/2 (deformation in Z direction/diameter)
Simulation carried out with the parameters received from layout of experiments from DOE software as shown in Table. The output (response) are deformation perpendicular to sheet surface (here Z direction) and bending angle. Simulation carried out for all 31 combinations from DOE. Some of the simulation

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results are shown here.

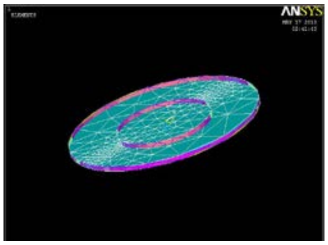

Figure 2.5: Deformation of circular sheet (thickness 0.2 mm, beam diameter 0.2, temperature 700K, pressure 0.05 N/mm2)

DOE & Analysis in Ansys:

A response surface methodology has been used to analyses the effects of parameters

Response Table:

Thickness (mm)	Beam Diameter(mm)	Temperature(K)	Pressure(N/mm²)
0.1-0.5	0.1-0.5	600-1000	0.4-0.8

Deformation in Z Direction(mm)
0.023794
0.016881
0.023794
0.020952
0.01941
0.02394
0.029052
0.029052
0.033157
0.013567
0.024157
0.033224
0.01857
0.05913
0.023794
0.02415
0.024136
0.042036
0.016879
0.021221
0.019437
0.033945
0.024169
0.029924
0.014515
0.02145
0.02112
0.037439
0.024228
0.023551
0.029924
Bending Angle(Degree)
9.01
9.58
8.013
11.8
10.98
13.46
10.96
16.19
12.46
15.18
13.58
9.43
7.05
30.59
9.01
9.14
13.56
11.86
9.58
6.05
3.707
4.85
13.57
4.29
1.66
4.03
4.02
4.28
3.46
3.36
4.27

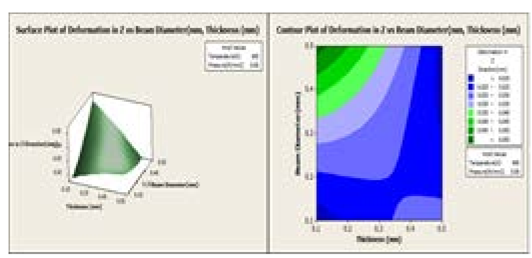

Figure 2.6: Plots for beam diameter and thickness v/s deformation (a) surface plot (b) contour plot

3 Conclusion & Future-scope

The studies using FE simulation following conclusions are drawn:

Low thickness and high beam diameter have high deformation. It is greater than 0.050mm. Thickness low and in medium range (700-900K) temperature deformation is high. The deformation is more than 0.025 mm at 0.4mm thickness and 700 to 900K temperatures. Low thickness (0.1mm) and high vacuum (0.04N/mm2) gives high deformation.

The deformation has values greater than 0.03mm. Higher temperature and higher beam diameters gives highest deformation. The values are more than 0.036mm. Higher value of vacuum and beam diameter gives best possible result for deformation. The values of is more than 0.035. The higher vacuum and higher temperature gives highest value of deformation. The values are more then .032mm. Among these all results the best possible result for deformation is getting by combination of low thickness and high beam diameter. Low thickness and high beam diameter gives better bending angle. The values of bending angle more than 15 degree.

The higher temperature and lower thickness gives higher bending angle. The values of bending angle more than 12 degree. Low thickness and high vacuum gives higher values of bending angle. The values are more than 12 degree. Low beam diameter and high temperature gives higher values of bending angle. The values are more than 17.5 degree. Higher vacuum and lower beam diameter gives higher degree of bending angle. The values are more than 17.5 degree. Higher vacuum and higher temperature gives higher value of vacuum. The values are more than 14 degree. Among these all results the best possible result for bending angle is getting by combination of higher vacuum and low beam diameter.

FE analysis study for effect of thermal conductivity on formability.

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