Proceedings of 10th International Conference on Precision, Meso, Micro and Nano Engineering (COPEN 10)
December 07 – 09, 2017, Indian Institute of Technology Madras, Chennai – 600 036 INDIA

Investigation on Deformation Mechanism in Laser Forming of a Bowl Shaped Surface out of a Flat Circular Thin Sheet using Circular Scan

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Abstract

Being a precise non-contact thermal forming technique, laser forming can not only compliment mechanical forming process by correcting the residue errors of the latter, it has also alone emerged as a technique for prototype making and small lot production, in aerospace, microelectronics, automobile and ship building industries. In order to alleviate product rejection after such a secondary or tertiary processing stage and that too avoiding time and resource consuming test trials, finite element (FE) analysis is used as an important tool. Due to process characteristics, generation of a smooth bowl shaped surface by laser forming is always a challenge and still significant numbers of research papers are being published on this topic. This work attempts FE analysis of bowl shape forming out of a flat circular sheet using multiple circular scan passes in order to reveal underlying deformation mechanism. Deformation predicted by simulation matched fairly well with experimental observation. Tangential stress component in the sheet being formed has been noticed, which is responsible for the asymmetry in the laser formed bowl shaped surface, because upon crossing a critical value it causes buckling of the thin sheet. Despite higher resistance to bending due to the geometry of the circular sheet blanks, counter bending was found to take place similar to bending of rectangular sheets by temperature gradient mechanism of laser forming.

Keywords: Thermal forming, FE analysis of thermo-mechanical problem, three dimensional surfaces

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1. INTRODUCTION

Mechanical forming processes involve exertion of mechanical force onto the sheet/blank being formed through direct contact of mechanical parts like die-punch etc. These are associated with the problems like relaxation of deformation through spring-back that becomes a serious concern when the total deformation to be imparted is quite small. Besides, fragile, brittle and small parts are difficult to be formed mechanically. On the other hand, a thermal source like an oxy-acetylene flame or a laser can deform a work-piece by inducing non-uniform strain within it through localized heating, without mechanical contact and thus also minimizing work-piece handling. Laser is specially used for precise forming of thin sheets, often in integration with laser cutting and/or laser welding.

Laser forming can be realized mainly through three distinct mechanisms - temperature gradient mechanism (TGM), upsetting mechanism (UM) and buckling mechanism (BM) [1]. The temperature gradient caused by laser beam interaction at the cross section of the sheet, perpendicular to the laser scan path, along with the sheet thickness determines which mechanism will be dominant. When a steep temperature gradient is established material layers closed to the laser irradiated surface tries to expand due to being at higher temperature. Colder layers beneath it restrict this expansion and convert a part of it into plastic compression. This, on cooling of the sheet results in bending towards the laser beam. This is TGM. When, nearly uniform temperature distribution is attained along thickness direction, plastic compression of the heated sheet portion, by the cold materials at sides, results in thickness increment at the expense of decrease in width transverse to scan path. This is UM. In case of thin sheets, under heating conditions similar to UM, buckling takes place due to the sidewise compressive force and bends the sheet away from the laser beam. This is BM. Fourier no. $F = \kappa d/h^2 v$, where, κ, d, h and v are thermal diffusivity, laser spot diameter, sheet thickness and scan speed respectively. This is greater than unity in case of BM and UM, but, less than unity in case of TGM.

Laser forming is employed for correction of residue error left over by mechanical forming processes and also for generation of developable and non-developable surfaces. Forming a developable surface necessitates bending about multiple straight lines, while both bending and shrinkage are needed for laser forming of a non-developable surface. Forming a bowl shaped surface out of a flat circular sheet is a classic example of laser forming of a non-developable surface. In mechanical forming, like say deep drawing, the entire sheet is altogether deformed while in laser forming, only a part of the sheet undergoes deformation at a moment. This greatly enhances the chances of asymmetry in the later process. This problem is further multiplied by the inherent asymmetry of laser forming process associated with the laser beam movement. Therefore, bowl shape forming is a challenge in the domain of laser forming. Till recent time several research papers dealt with this topic [2-7].

Watkins et al. [2] claimed that concentric circular scan lines with laser parameters suitable for UM is the best scan strategy for laser forming of a bowl shaped surface. Scan paths closer to the centre needs to be scanned first. In contrary, Hennige [3] suggested for using a set of circular scan paths with parameters suitable for TGM and a set of radial scan paths with parameters suitable for UM for laser forming of a bowl shaped surface. Chakraborty et al. [4] carried out a detailed investigation on laser forming of a bowl shaped surface with circular and radial laser scan lines as suggested by Hennige [3]. They found that circular scans at higher radius produced more bending angle and less coefficient of variation (CV) of bending angle. CV of bending angle is a measure of asymmetry in the formed bowl

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ISBN: 978-93-80689-28-9

shape. The bending angle formed by radial laser scans had less CV as compared to the circular scans. A combination of radial and circular scan schemes works better in producing a deeper bowl shaped surface retaining symmetry. Scans close to the periphery of the circular sheet blank should be executed first. Through finite element (FE) simulations of laser scan along different scan paths to form cap (similar to a bowl) shaped surface, Gollo et al. [5] showed that full Fermat's scan path can produce more symmetric bowl shaped surface, although higher height and curvature of the formed cap shaped surface could be achieved with Archimedean spiral starting from the centre. However, the sheet used by them was relatively thicker and hence less prone to asymmetry after forming due to buckling or warping. Chakraborty et al. [6] suggested for laser irradiation surrounding the centre of a circular sheet blank with a large spot diameter and sufficient power density to form a bowl shaped surface. Higher symmetry in the laser formed bowl shaped surface could be attained by symmetrical heating and doing away with the asymmetry posed by laser beam movement. However, for laser forming of large blanks this technique may not be feasible as it will be difficult to avail sufficient power density at a large spot diameter required in this case.

Recently, Tavakoli et al. [7] found out optimum radial scan paths set for laser forming of a uniform bowl shaped surface. As compared to circular scan paths radial scan paths can ensure more symmetry and uniformity as established from the findings of Chakraborty et al. [4]. However, radial scans are carried out at slower speed to facilitate UM. Also, a large number of scan paths are required for bowl shape forming. Compared to that circular scans are faster to realize TGM and produces high bending per pass. Therefore, to cut down time required to laser-form a deep bowl shaped surface a combination of radial and circular scans are must. Now-a-days more impetus is given on structural weight reduction of automobile etc. through the use of thin sheets (thickness ~ 1 mm) of high strength materials. However, efforts are rare to investigate laser forming of a complete bowl shaped surface out of a thin sheet (more prone to buckling and resultant warping) using FE simulation. In order to alleviate product rejection after such a secondary or tertiary processing stage like laser forming and that too avoiding time and resource consuming test trials, finite element (FE) analysis is an useful tool. It can reveal the insight of deformation mechanism and provide necessary guidelines to avoid asymmetry in the formed surface.

This work contains FE simulation of laser forming of a bowl shaped surface using multi-pass circular scans at 30 mm radial distance from the centre of a 1 mm thick flat circular blank of AISI 304 stainless steel having 100 mm diameter. The simulation results have been compared with their experimental counterparts. Experiments were performed on a 2 kW Yb fibre laser (wavelength 1.07 µm) workstation. Laser displacement sensor (Micro Epsilon make, model: Opto NCDT 1402) mounted on a three axes translation stage and connected to a digital multimeter (APPA make, model: 505) was used for measuring relative displacement among any two points on the laser formed surface. Nine circular scan passes were executed at the same path to generate bending angle that can be measured without significant error. Three consecutive circular scan passes were started at 120° angular separation from each other. Such a set of 3 paths were offset from each other by 30° as done in [4] for better symmetry of the formed surface. A portion of the scan path equal to laser spot diameter were not irradiated to prevent deposition of additional energy during start and end of scan. The bending angle measurement principle, as followed in [4], was used. It is illustrated in Fig. 1.

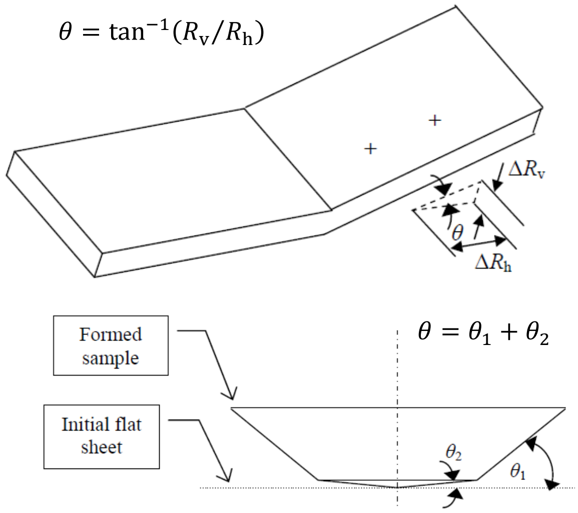

Fig. 1. Principle of bending angle measurement.

2. FINITE ELEMENT SIMULATION

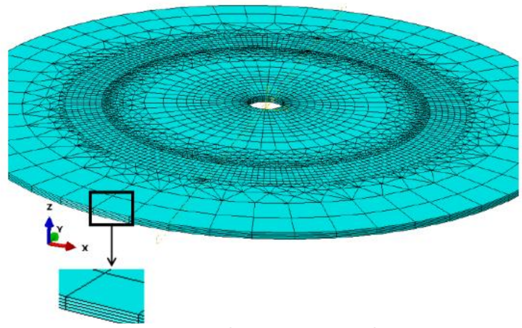

Fig. 2. Mesh used for simulation of laser scan.

Laser forming has been simulated as a sequentially coupled transient thermal-static structural problem with the assumption that plastic deformation does not affect the temperature distribution. Commercial FE software ABAQUS 6.10 was used for carrying out the simulation. Fig. 2 shows the mesh, selected based on initial trials for convergence, for the FE simulation. A region spanning 6 mm transverse to the scan path has been meshed with finer hexagonal elements for accuracy. This dimension includes spot diameter and thermal diffusion length. This finely meshed region is surrounded by regions, meshed with tetragonal elements, which blend the finely meshed region with inner and outer most regions coarsely meshed with hexagonal elements. This strategy of meshing was used to reduce computational time. All elements were linear. The material was assumed to follow linear kinematic hardening. Temperature dependent material properties and non-uniform laser beam intensity distribution as contained in [8] have been used. Only one set of three consecutive circular scan passes were simulated. Absorptivity was measured to be 0.4 with the help of a power meter (OPHIR make, model: COMET-10K-V1 ROHS, accuracy ±5%).

3. RESULTS AND DISCUSSION

Table 1 summarizes the laser parameters and the bending obtained in the simulation and the experiment.

Table 1. Results obtained in simulation and experiment

Laser parameters	Bending angle (°)			Coefficient of variation (CV) of bending angle		
	Simulation		Experiment (cumulative of 9 passes)	Simulation		Experiment (cumulative of 9 passes)
Spot diameter = 2 mm	After 1st scan	0.55	2.34 (0.26° per pass on average)	After 1st scan	0.04	0.17
Laser power = 750 W	After 2nd scan	0.71		After 2nd scan	0.02	
Scan speed = 5.5 m/min	After 3rd scan	0.74		After 3rd scan	0.02	

As seen in Table 1 for the initial pass in simulation we get bending angle (0.55°) quite high as compared to average bending angle per pass (0.26°) obtained in the experiment. However, cumulative bending angle after 3 passes predicted by simulation (0.74°) is close to 3 times of the average bending angle per pass (0.78°) obtained experimentally. However, CV of bending angle predicted was a few times lesser than its experimental counterpart. To form a bowl shape out of a flat circular sheet-blank the region in the outer side of the scan line has to shrink tangentially. Only elastic deformation is not sufficient to provide enough shrinkage so that high bending angle can be realized. Experimentally, high bending angle can be obtained as the sheet warps or buckles due to high tangential compressive stress. Therefore, CV of bending angle was also high. In simulation within the 3 passes buckling is not seen, the bending is nearly axi-symmetric with very less CV. Therefore, bending angle also increased very little in the second pass and almost no increase in bending angle could be achieved in the third scan pass. With further scan passes tangential stress sufficient to cause buckling may be reached. Buckling being an instability may be sensitive to the mesh used; an irregular mesh may promote buckling. Hybrid formulation approach was considered, that may suppress buckling by making the model stiffer against it. In simulation the sample was assumed to be initially stress-free while the sheet used in experiment may have residual stress. Besides, effect of strain rate has not been considered. The sheet material has been assumed to have linear kinematic hardening, while the actual hardening behaviour may be more complex. These may be sources of error in prediction through the simulation. Fig. 3 shows the distribution of vertical component of displacement i.e. displacement perpendicular to the plane of specimen. Vertical displacement after second and third scans are almost similar for the reason mentioned above. After cooling after the third pass vertical displacement reduced a little. This may be due to partial relaxing of the initial compression of the irradiated surface by cold bottom layers. When the bottom layer tries to expand after receiving heat, it forces the top layer to expand with it and in this process it relaxes partially the initial compression it induced on the latter at the start of laser irradiation.

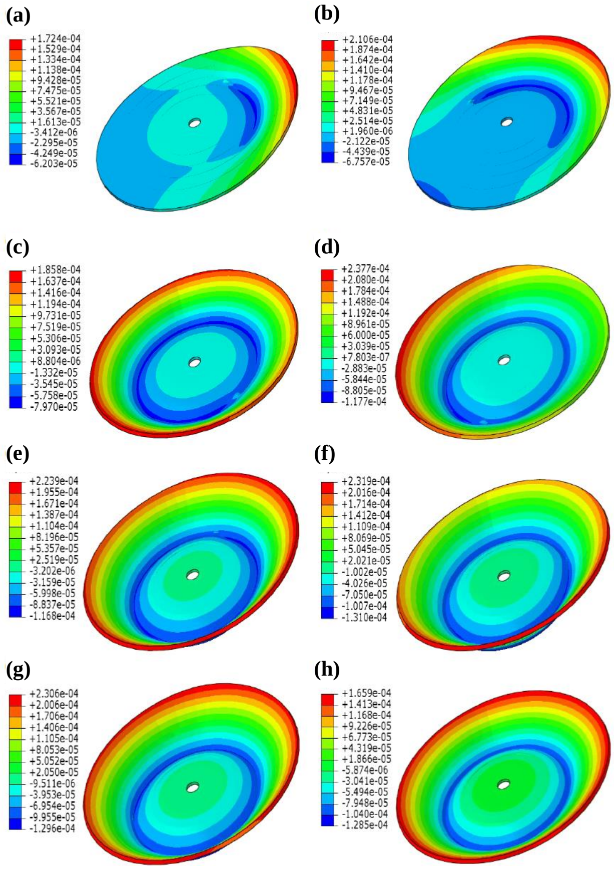

Fig. 3. Vertical displacement due to laser scan at (a) quarter of 1st scan, (b) half of 1st scan, (c) end of 1st scan, (d) 1 and half scan, (e) end of 2nd scan, (f) 2 and half scan, (g) end of 3 scans, (h) at the end of cooling. Deformation is 50 times magnified for clarity.

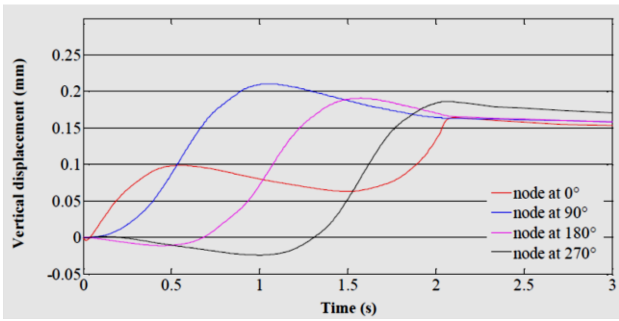

Fig. 4. Vertical displacement of peripheral nodes at 0°, 90°, 180° and 270° angular position relative to the starting (and ending) point of 1st circular laser scan during laser scan and subsequent cooling

One may be curious to know whether in case of bending of circular blank using TGM, initially bending away from the laser beam known as counter-bending, as observed in case of bending of rectangular samples, happens or not. Unlike rectangular sheets here constrains to bending are quite high due to the shape of the samples. Vertical displacements of 4 peripheral nodes separated by 90° angle obtained during the first scan are plotted in Fig. 4. Here, the scan starts near to the node at 0°. As evident, a small counter-bending continued for quite a long time at the node (node at 270°) towards the end of scan path. Vertical displacement versus time plot at the node at which the scan started and ended is different from other three nodes.

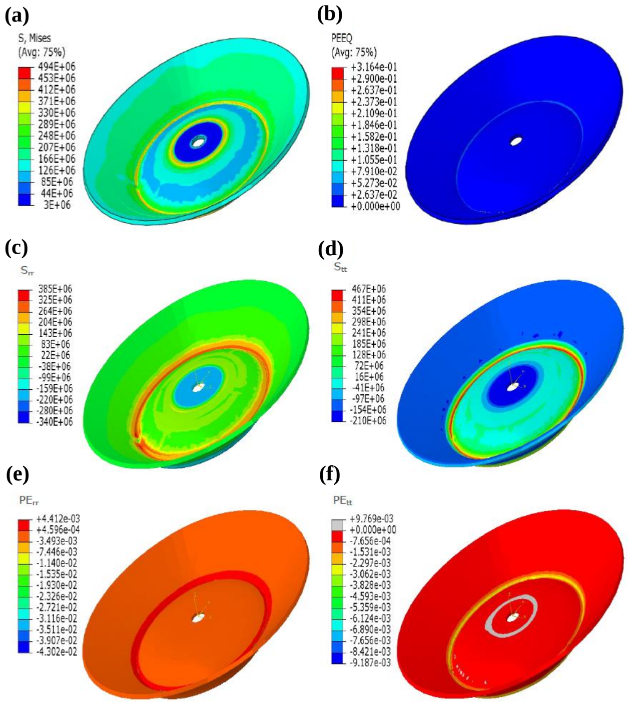

Fig. 5. (a) von Misses stress, (b) plastic equivalent strain, (c) radial stress, (d) tangential stress, (e) radial component of plastic strain and (f) tangential component of plastic strain, after laser forming by 3 consecutive circular scan passes. Deformation is 50 times magnified for clarity.

Fig. 5(a) shows distribution of von Misses stress on the specimen formed by 3 circular scan passes. Fig. 5(b) depicting the plastic equivalent strain after forming reveals that deformation is highly localized which is often a key feature of laser forming process. Fig. 5(c) and (d) respectively show distribution of radial and tangential stress after forming. Clearly, except the scan track almost the entire formed specimen is under compression along tangential direction. The laser irradiated surface is under compression both tangentially and in the radial direction. High compressive tangential stress is seen at the region outer to the scan path as well as close to clamping at the end of forming (Fig. 5(d)). This compressive stress if crosses a critical limit may cause buckling that may warp the specimen. That would be revealed through high values of CV of bending angle. Distribution of radial and tangential plastic strains is shown in Fig. 5(e) and (f) respectively. The scan track has tensile and compressive plastic strains in the radial and tangential directions respectively. Close to the annular surface around the central hole that was constrained against displacement along and rotation about all axes, tangential plastic strain is tensile while it is compressive in rest of the sample. Higher laser power (800 W) and lower scan speed (5 m/min) at the same radius of circular scan path resulted in higher bending angle (3.4°) but increased CV which hints at the presence of higher tangential stress. At the same laser parameters higher bending angle and lower CV was obtained for higher circular scan path radius and vice versa (see Table 2). Even for the same bending angle, for higher circular scan path radius, the amount of material (towards the periphery of the sample and outside the scan path) to be shrunk is less resulting in lesser tangential stress and hence lesser CV.

Table 2. Experimental results at different circular scan path radius

Scan path radius (mm)	Bending angle (°)	CV
40	4.0	0.08
20	1.4	0.17

4 CONCLUSIONS

FE simulation on laser forming of a bowl shaped surface out of a flat circular sheet, with multiple circular scan passes using TGM, hinted that pass-by-pass bending may be non-uniform due to buckling phenomena. Except the scan track almost the entire formed specimen was found to be under compression along tangential direction. Presence of high magnitude of the tangential stress component in the formed sheet showed the possibility of the onset of buckling. It was further revealed that, despite higher resistance to bending due to the geometry of the circular sheet blanks, counter bending takes place similar to bending of rectangular sheets by TGM. However, the magnitude may be lesser.

Future numerical models may consider temperature dependant absorptivity for capturing the physics of the process better.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the help and support of the Mechanical Engineering Department, IIT Kharagpur in carrying out the work reported.

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