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Laser forming of a bowl shaped surface with a stationary laser beam

Shitanshu Shekhar Chakraborty, Harshit More, Ashish Kumar Nath *

Department of Mechanical Engineering, IIT Kharagpur, Kharagpur 721302, India

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A B S T R A C T

Despite a lot of research done in the field of laser forming, generation of a symmetric bowl shaped surface by this process is still a challenge mainly because only a portion of the sheet is momentarily deformed in this process, unlike conventional sheet metal forming like deep drawing where the entire blank undergoes forming simultaneously reducing asymmetry to a minimum. The motion of laser beam also makes the process asymmetric. To counter these limitations this work proposes a new approach for laser forming of a bowl shaped surface by irradiating the centre of a flat circular blank with a stationary laser beam. With high power lasers, power density sufficient for laser forming, can be availed at reasonably large spot sizes. This advantage is exploited in this technique. Effects of duration of laser irradiation and beam spot diameter on the amount of bending and asymmetry in the formed surface were investigated. Laser power was kept constant while varying irradiation time. While varying laser spot diameter laser power was chosen so as to keep the surface temperature nearly constant at just below melting. Experimental conditions promoted almost uniform heating through sheet thickness. The amount of bending increased with irradiation time and spot diameter. It was interesting to observe that blanks bent towards the laser beam for smaller laser beam diameters and the reverse happened for larger spot diameters (~10 times of the sheet thickness). Effect of spot diameter variation has been explained with the help of coupled thermal-structural finite element simulations.

1. Introduction

Laser forming is a flexible, non-contact forming technique that can be easily automated, can form hard and brittle materials and can be integrated with other laser processing techniques like cutting, welding, etc. The forming of materials having finite thermal expansion coefficient, takes place by this process due to deformation caused by localised heating with laser irradiation. Three main mechanisms of this process are temperature gradient mechanism (TGM), buckling mechanism (BM) and upsetting mechanism (UM) [1]. TGM bends the sheet towards the laser beam with negligible shrinkage (accompanied by thickness increment) of the heated zone. BM causes out-of-plane bending away from the laser beam for a stress free material without pre-load. UM when activated using two laser beams, heating at the top and bottom of the sheet causes only shrinkage of the heated portion [2]. Apart from these Shi et al. [3] have proposed another mechanism called coupling mechanism (CM). CM being a superimposition of TGM and UM can result in simultaneous bending and shrinkage. Steep temperature gradient is required for TGM to dominate; whereas to activate UM and BM, near uniform heating through the sheet thickness is recommended. Fourier number (F), a form of dimensionless time, indicates the temperature gradient along the sheet thickness established during interaction of the laser beam with a cross section perpendicular to the scan path. It is given as $F=\kappa\tau/h^2$ where, κ, τ and h denote thermal diffusivity, laser interaction time and sheet thickness, respectively. For continuous wave laser scan, $\tau=d/v$, where, d and v are laser spot diameter and scan speed, respectively. For smaller values of Fourier number temperature gradient mechanism dominates; while, for larger values the other two mechanisms operate [4]. However, Shi et al. [5] showed that since the Fourier number does not involve laser power, it is not sufficient to dictate the dominant mechanism of laser forming. They derived the following condition for onset of buckling.

$$F_{\text{buckling}} \sim \frac{T_{\text{H}}^{\text{avg}}}{h^2/d^2} \geq \frac{\pi^3}{20.76(1+\mu)A\alpha_{\text{th}}} \tag{1}$$

where, $T_{\text{H}}^{\text{avg}}$, h, d, A, α_{th} and μ are the average temperature rise of the heated zone, sheet thickness, laser spot diameter, absorptivity, coefficient of thermal expansion and Poisson's ratio, respectively.

Laser forming of a symmetric non-developable surface like a bowl is difficult mainly because unlike conventional sheet metal

* Corresponding author. Tel.: +91 3222 281784; fax: +91 3222 255303.
E-mail address: aknath@mech.iitkgp.ernet.in (A.K. Nath).

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Nomenclature (with SI units)

A	absorptivity of laser beam
$\boldsymbol{b}$	body force per unit volume (N/m^3)
C	specific heat (J/kg K)
d	laser spot diameter (m)
F	Fourier number
$F_{buckling}$	parameter that indicates the possibility of buckling (K)
g	heat generated per unit volume due to plastic deformation (J/m^3)
h	sheet thickness (m)
K	thermal conductivity (W/m K)
P	laser power (W)
R	radius of laser formed bowl shaped surface (m)
T	temperature (K)
T_H^{avg}	average temperature rise of the heated area (K)
t	time (s)
$t_{instance}$	time instance (s)
V	sheet material domain
v	scan speed (m/s)
$\boldsymbol{x}$	position vector
α_{th}	coefficient of thermal expansion (/K)
ΔR_h	horizontal component of the radius vector at any peripheral point of the formed sample (m)
ΔR_v	vertical component of the radius vector at any peripheral point of the formed sample (m)
θ	bending angle (radian)
$\bar{\theta}$	average bending angle (radian)
θ_{CV}	coefficient of variation of bending angle
κ	thermal diffusivity (m^2/s)
μ	Poisson's ratio
ρ	density (kg/m^3)
$\boldsymbol{\sigma}$	Cauchy stress tensor
τ	laser interaction time (s)

forming where the entire blank is simultaneously deformed that minimises the asymmetry, in laser forming only a portion of blank is momentarily deformed. The motion of the laser beam also is an inherent asymmetric feature of the process. Several strategies have been proposed and explored by researchers for laser forming of bowl shaped surface [6–10]. Magee et al. [6] suggested for using concentric circular scan paths with laser parameters suitable for UM to form a bowl shaped surface. The scan lines were sequenced from lower to higher radius. Hennige [7] used circular scan lines with parameter combinations suitable for TGM and radial scan lines with parameter combinations favouring UM to generate bowl shaped surfaces. They recommended a sequence of radial scan line sets of different lengths and circular scan line sets at different radii for forming bowl shaped surfaces. The scan lines closed to the periphery of the flat circular blank were recommended to be scanned first. This was further corroborated by the observation of Chakraborty et al. [8] who investigated the effect of laser parameters and different circular and radial scan line sets on the average bending angle and its coefficient of variation (CV) in laser formed bowl shaped surfaces. Yang et al. [9] gave a strategy in which mutually perpendicular scan line sets were used for laser forming of bowl shaped surfaces. Gollo et al. [10] comparing radius of curvature and edge distortion for different scan paths through simulation showed that full Fermat's scan path can produce more symmetric bowl shaped surface, though Archimedean spiral starting from the centre generated higher height and curvature of the formed surface. However, none of these suggested strategies could avoid the aforesaid limitations of laser forming.

With the availability of high power laser systems, sheet metals can be formed even with large beam diameters at the work-piece inducing bending in one go. This advantage has been exploited in forming bowl shaped surface out of flat circular blanks of $\Phi 25 \times 1$ mm size AISI 304 steel sheet with a stationary laser beam irradiating at the centre of blank. The effect of laser irradiation time and laser spot diameter was observed on bending angle and its CV in the formed surfaces. The former one indicates the amount of forming while the latter represents the asymmetry in the formed surfaces. Bending angle increased for higher irradiation time under constant laser power and spot diameter. While varying spot diameter the laser power was chosen so as to keep the peak surface temperature of samples similar and just below melting, with the help of pilot experiments. This ensured high amount of forming of samples. Both bending towards and away from the laser beam could be observed while varying the spot diameter. Coupled thermal-structural finite element (FE) simulations were performed to explain these results. The process being axi-symmetric, FE simulations were carried out considering it as an axi-symmetric problem. However, to establish the validity of this assumption, three dimensional FE simulations have also been performed. To see the effect of intensity distribution of the laser beam on temperature distribution as well as deformation, axi-symmetric FE analyses have been carried out considering the uniform intensity distribution as well as approximated non-uniform intensity distribution of the laser beam used, as reported in [11].

2. Experimental details

Flat circular blanks of 25 mm diameter cut from as received 1 mm thick AISI 304 steel sheet were irradiated at the centre with a 2 kW Yb fibre laser (YLR 2000, IPG make). Irradiation time was varied from 1 to 4 s keeping laser spot diameter constant at 6 mm and power as 300 W. Further, laser spot diameter was varied from 6 to 12 mm keeping irradiation time fixed at 4 s. Laser powers while varying spot diameters were chosen so as to keep the peak surface temperature similar. Three dimensional FE simulations considering non-uniform intensity distribution of the laser beam (as discussed in Section 2) showed that the peak surface temperature varied in the range of 1513–1741 °C ($\sim$14% of the mean value in the range) while varying laser spot diameter which is higher than the liquidus temperature of the sheet material, AISI 304 steel (1454 °C [12]). However, no sign of melting of the samples could be observed visually in any case probably due to not fulfilling the requirement of latent of fusion for a significant amount of material. Blanks were coated with black ink with Camelin Artline marker for better absorption of the incident laser beam. The absorptivity of laser energy was estimated to be $\sim$0.6 with the help of a power metre (model: COMET-10K, OPHIR make). Blanks were placed on a fire-brick before being irradiated with the stationary laser beam. Displacement at the periphery relative to centre of the formed sample was measured at four locations with the help of a laser displacement sensor (model: Opto NCDT 1402, Micro Epsilon make). The average, $\bar{\theta}$ of the four measured angles, θ_1, θ_2, θ_3 and θ_4 is,

$$\bar{\theta} = \frac{1}{4}\sum_{i=1}^{4}\theta_i, \qquad \theta_i = \tan^{-1}\left(\frac{2\Delta R_h^i \Delta R_v^i}{\Delta R_h^{i2} - \Delta R_v^{i2}}\right) \tag{2}$$