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Thermo-mechanical finite element study on deformation mechanics during radial scan line laser forming of a bowl shaped surface out of a thin sheet

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ABSTRACT

Forming a smooth bowl shaped surface out of a flat circular sheet-blank requires tangential shrinkage which can be met well with radial laser scan lines placed in proper sequence as suggested by previous researchers. However, few studies look into the finite element analysis of laser forming of the entire bowl shaped surface from a flat circular thin sheet which could provide a better insight of the forming mechanism. Therefore, in this work the laser forming of a bowl shaped surface with radial laser scan lines has been investigated with the help of finite element simulation. This revealed that the bending of the sheet by radial scan does not take place only because of thickness increment at the radial scan tracks due to shrinkage, but also because of a localized buckling about the radial scan lines. Irregular meshing, reduced integration scheme and higher number of linear elements along the sheet thickness direction could provide a better matching of the simulation results with their experimental counterparts. Accuracy of prediction of the simulation results was also found to be sensitive to the tangent modulus of the assumed linear kinematic hardening model.

1. Introduction

Laser forming is a non-conventional forming technique that is mainly used to deform sheets of various metals, such as stainless steels, alloys of aluminium, magnesium and titanium etc. which have a high coefficient of thermal expansion. Important advantages of this non-contact process are flexibility, amenability to automation and ability to form hard and brittle materials. Laser forming operates mainly through three different mechanisms; they are temperature gradient mechanism (TGM), upsetting mechanism (UM) and buckling mechanism (BM). TGM bends the sheet towards the laser beam, UM should ideally cause only in-plane shrinkage while a stress free sheet usually bends away from the laser beam when BM dominates. Fourier number that indicates temperature gradient along any cross section perpendicular to the scan path, corresponding to a combination of laser parameters, usually determines the mechanism that will be dominant. For continuous wave (CW) laser scan Fourier number, $F = \kappa d/h^2 v$ where, κ, d, h and v are thermal diffusivity of the sheet material, laser spot diameter, sheet thickness and scan speed respectively. To facilitate TGM F should be less than unity and it should be the reverse for letting the other two mechanisms to dominate. Apart from extensive research on effect of laser processing parameters [1–3], sheet geometry [1,4,5], material properties [1,6] and additional assist mechanical force [7], researchers have also focussed their attention towards three dimensional laser forming [1–15] and modelling of laser forming process [16–24].

Hennige [8] suggested for using circular and radial scan lines with parameters suitable for TGM and UM respectively for laser forming of a bowl shaped surface out of a flat circular sheet. Yang et al. [9] suggested for using laser scan lines parallel to the edges and diagonals of a square and rectangular sheet to form a pillow shaped surface. They named it 'cross spider strategy'. Radial scan lines extending from the centre to the edges produced a saddle shaped surface. Edwardson et al. [10] represented the surface to be formed as a combination of Bezier surface patches and used the gradient vectors to obtain an iterative forming strategy. Liu and Yao [11] suggested a scan strategy based on the in-plane strain and bending strain requirement to form a surface curved about two axes, out of a flat sheet blank. Kim and Na [12] discretized the target surface into plane patches and calculated relative bending and shrinkage required among the patches. Next, they obtained laser power and scan speed required to impart the necessary bending and shrinkage among patches from a prior prepared database obtained by

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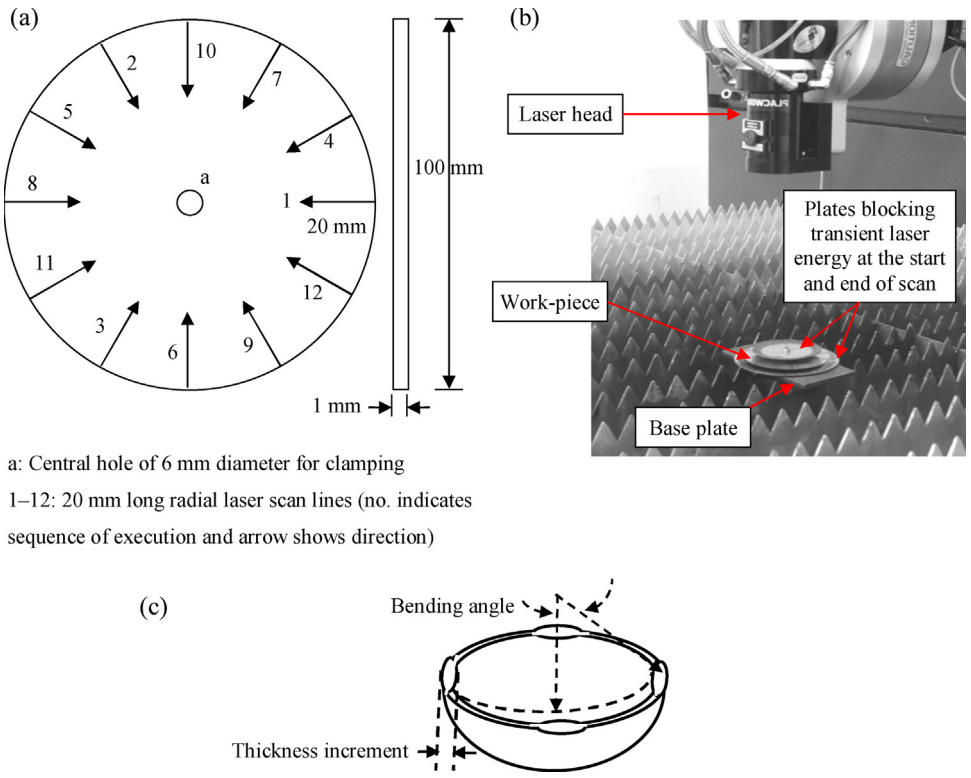

Fig. 1. (a) Radial scan lines on the work-piece, (b) experimental set-up, (c) schematic of a typical laser formed bowl shaped surface as per previous literature (thickness increment has been exaggerated for better visibility).

finite element (FE) analysis of laser forming of a standard specimen. Chakraborty et al. [13] suggested a strategy modifying the 'cross spider strategy' for laser forming of deeper pillow shaped surface retaining better symmetry. Among different scan-path-strategies tried by Gollo et al. [14], based on comparison of radius of curvature and edge distortion, full Fermat's scan path was found to produce more symmetric bowl shaped surface; though Archimedean spiral starting from the centre was found to generate higher height and curvature of the laser formed bowl shaped surface. Chakraborty et al. [15] proposed using symmetric laser irradiation at the centre of a circular sheet-blank with a stationary laser beam for laser forming of a bowl shaped surface with better symmetry. However, such heating by a defocused laser beam may demand quite high laser power specially for forming a sheet having large diameter/thickness.

Significant efforts have been made to model laser forming process analytically, as well as with finite element method and empirical techniques [16]. Shen et al. [17] developed an analytical model for estimating bending angle that calculates plastic deformation during both heating and cooling phase of laser forming process based on history dependent incremental stress-strain relationship. The model predicted bending angle with good accuracy for laser forming parameters under both TGM and BM. Zhang and Michaleris [18] showed that the angular deformation, caused in laser bending of rectangular samples, was over predicted using the Eulerian approach in FE analysis; though it took several times less computational time as compared to the Lagrangian approach that gave accurate prediction. Examining the convergence of numerical simulation with increased discretization, Zhang et al. [19] found the minimum requirements for spatial and temporal discretization of 3D finite element models for laser bending of shipbuilding steel AH36 (304.8 mm × 304.8 mm × 19.05 mm). They concluded that two quadratic solid elements per radius of laser beam along with three quadratic elements through thickness for spatial discretization and four time increments for a movement by laser beam radius for temporal discretization was sufficient. Through numerical simulation on the effect of various pre-loads viz. pure tension, pure compression and pure bending favouring bending towards and away from the laser beam, Yao et al. [20] showed that pure compression and pure bending can increase the bent angle towards the laser beam, while the pure tension and pure bending can decrease bent angle away from the laser beam. Shen et al [21] carried out FE analysis of laser forming of metal/ceramic bi-layer plate of Al 6061/SiC. They showed that residual tensile stress prevailed at both the top and bottom surfaces and there were compressive stresses at the interface between two materials. Peng et al. [22] through finite element simulation of deformation of ring segments observed that with the increase of laser beam diameter, the differences in displacement of three points, one at middle and others at extreme edges of the curved scan path, decreased and, with the increase of central angle this difference at first decreased (around 50° angle) and then increased (around 90° angle).

From the results reported in [23] it is clear that radial laser scan lines with laser parameters suitable for UM can produce more symmetric bowl shaped surface. The reason is: to form a bowl shaped surface out of flat circular sheet, shrinkage in periphery i.e. tangential shrinkage is required. This can be provided by the radial scan lines with laser parameters suitable for UM. Localized deformation mechanism of laser forming process and asymmetry associated with the laser beam movement are barriers to retain symmetry of laser formed symmetric surfaces like a bowl shaped surface. However, FE analysis of laser forming of a complete bowl shaped surface from a thin flat circular sheet is rarely reported. It is important because as shown in [23], compared to annular and circular segments forming of entire circular thin sheet into a bowl shape is more difficult. Gollo et el. [14] carried out FE analysis of different scan path strategies like full Fermat's path, Archimedean spiral etc. Recently, Tavakoli et al. [24] reported simulation results