Journal of Materials Processing Technology 222 (2015) 128–141

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Modification of bent angle of mechanically formed stainless steel sheets by laser forming

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ARTICLE INFO

Article history:
Received 17 October 2014
Received in revised form 25 February 2015
Accepted 27 February 2015
Available online 14 March 2015

Keywords:
Laser forming
Correction of bending angle
Temperature gradient mechanism
Fourier number
Laser spot diameter
Finite element modelling

ABSTRACT

Laser forming, being a flexible non-contact forming technique, is an attractive tool for the correction of spring back, over-bending or distortion of sheets formed mechanically or by other means. However, literatures are scarce on this topic. This work investigates the modification of bent angle of mechanically formed stainless steel blanks by laser forming using experiments and finite element (FE) simulations. Changes in angle imparted by laser forming, in specimens bent with the help of different die-punch combinations, have been studied for different Fourier numbers and laser spot diameters. Laser parameters were decided with the help of an analytical model so as to keep the peak surface temperature due to laser scan nearly constant for all the laser scan parameter combinations. Laser forming was carried out by scanning laser beam on both concave and convex sides of the mechanically bent specimens. The change in bent angle was found to be significantly larger when laser was scanned on convex side than on concave side. Further, for laser scanning on convex side, the change in bent angle increased with initial bent angle. Opposite trend was observed for laser scan on the concave side of the bending edge. However, for the similar mechanically bent angle, change in bent angle increased for laser scan on the concave side with increasing punch radius. For laser scan on the convex side the trend was just the opposite. Laser scans corresponding to different Fourier numbers did not significantly affect the change in bent angle. However, increase in laser spot diameter increased the change in bent angle. These observations were explained with the help of FE simulations considering temperature dependent material properties and multimode intensity distribution of the laser beam. Simulation results matched fairly well with their experimental counterparts in most of the cases.

1. Introduction

Laser forming is an attractive technique for rapid prototyping and correction of formed parts in automobile, aerospace and microelectronics industry as this is a tool-less, flexible process amenable to automation and has the capability to form even brittle materials. The three main mechanisms used in laser forming are temperature gradient mechanism, upsetting mechanism and buckling mechanism. When temperature gradient mechanism is the dominant mechanism, the sheet bends towards the laser beam. Buckling mechanism causes bending either towards or away from the laser beam depending on the external mechanical loads, residual stress, etc. In upsetting mechanism, ideally only in-plane shrinkage occurs. Fourier number that indicates the extent of heat diffusion along the sheet thickness during laser irradiation mainly controls which mechanism will dominate during laser forming. Fourier number $F = \kappa d/h^2 v$, where κ, d, h and v are the thermal diffusivity of sheet material, laser spot diameter, sheet thickness and laser scan speed, respectively, for continuous wave laser scan. It should be less than unity for temperature gradient mechanism to dominate. But to realise buckling mechanism and upsetting mechanism the condition is just the opposite, i.e. $F > 1$. As highlighted by Lawrence et al. (2001) laser spot diameter should be of the order of sheet thickness to realise temperature gradient mechanism and upsetting mechanism, whereas it should be much larger than sheet thickness for buckling mechanism to occur. In laser forming of 0.8 mm thick 07 M20 steel sheets using high power diode laser they observed 0.1°–3° bending angle per pass using temperature gradient mechanism. However, with buckling mechanism, bending angles as high as 15° were generated.

Wu and Zheng (2001) studied the effects of process parameters, material properties and sheet dimensions in laser bending of rectangular sheets. They found that bending angle increased with increasing laser power, decreasing laser spot diameter and decreasing scan speed. Among the sheet dimensions thickness was found to affect bending angle the most followed by sheet

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http://dx.doi.org/10.1016/j.jmatprotec.2015.02.044
0924-0136/

dimensions along and perpendicular to the scan path. Bending angle decreased for higher sheet thickness and increased for higher sheet dimension along the scan path. The other dimension did not significantly influence the bending angle. Yau et al. (1998) found that there was a threshold laser power for each scan speed below which no bending was observed, and an upper critical laser power at which bending angle saturated. This observation was explained by McBride et al. (2005) with a mathematical model. According to the model, on heating, when a particular temperature T_f is reached at the top surface, plastic compression is induced and bending angle increases with increasing value of energy input until a limit when a higher temperature T_{sat} is reached, at which the top surface develops counter plastic strain during cooling.

Different generalised approaches to form 3D non-developable surfaces were proposed by Edwardson et al. (2005), Liu and Yao (2005), and Kim and Na (2009). Edwardson et al. (2005) represented the surface to be formed as Bezier surface patches and used the gradient vectors to obtain an iterative forming strategy. Liu and Yao (2005) gave a scan strategy in which the strain distribution within the sheet after forming is obtained using finite element method (FEM). Laser scan paths have to be placed perpendicular to the principal minimum strain at any point. A database of in-plane and out of plane strains caused by different laser power and scan speed combinations has to be prepared using FEM. The laser power and scan speed required to fulfil the in-plane and out-of-plane strains requirements to form the desired surface are obtained from this database. Kim and Na (2009) discretised 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 the patches from the prior prepared FEM database.

Mechanical forming suffers from the disadvantage that even after using in-process control spring back angle cannot be eliminated completely, which is of significant concern for near net shape forming (Magee and De Vin, 2002). Besides, some inaccuracies are often left to the work-piece after mechanical forming, for example, due to possibility of collision with the mechanical parts of equipment often the over-bending of work-piece cannot be cost effectively done to counter the spring back (Magee and De Vin, 2002). Magee and De Vin (2002) showed how laser forming technique can be effective in addressing such limitations left over by mechanical forming. Dearden et al. (2006) demonstrated flattening of bent sheets by laser forming using an iterative approach, where the error between the desired shape and the shape obtained after previous pass was used to give a new scan strategy for subsequent passes. Ueda et al. (2009) applied upsetting mechanism of laser forming to flatten an intentionally imparted spherical protrusion on carbon steel and stainless steel sheets. For this they used four radial scans at 90° apart, directed from the periphery towards centre of the projected circular area of the spherical protrusion. Gisario et al. (2011) studied spring back control of AA 6082 T6 aluminium alloy sheet, bent in built-ad-hoc mould, by laser forming with a high power diode laser. Mechanically bent samples were held constrained in the mould while laser was scanned on the convex side of bending edge with parameters suitable for buckling mechanism. Effects of deflection during mechanical bending, laser power, scan speed, number of laser scan passes and laser spot area on the change in bending angle induced by laser forming of the constrained bent samples were studied. Amongst the parameters, they found laser power and number of scan passes to be the most influential. Further, they observed both partial compensation of the spring back and over-bending to occur for the bent samples depending upon the laser fluence and number of scan passes. However, angle modification by laser forming without removal of constraints may not always be possible. It may be because of the two facts – difficulty in accessing the bent region by laser beam or the lack of knowledge of the amount of modification to be incorporated. Besides, such a technique of using conditions for buckling mechanism along with laser scan on a single side of the bending edge of work-piece cannot every time guarantee angle modification in the desired direction, i.e. towards increasing the initial bending or to reduce it. Buckling mechanism suffers from another disadvantage – typical bending angle per pass is usually much higher than that generated in temperature gradient mechanism. Therefore, for bent angle modification by a smaller amount temperature gradient mechanism is better. However, there is a lack of in-depth study of bending angle modification of bent samples by temperature gradient mechanism of laser forming.

Effects of laser scan parameters on bending angle modification of bent sheet made of stainless steel, which is widely used and has different hardening behaviour compared to aluminium alloys has not been investigated earlier. Further, there is a lack of research effort towards investigating effects of parameters of mechanical bending of sheets like punch radius, bent angle, etc. on bent angle modification by laser forming. There is also a dearth of literature studying the difference in change of bending angle due to laser scan on convex and concave sides of the bending edge of bent samples. This work investigates the effects of bent angle (mechanically formed), punch-radius (used for mechanical bending), side of bending edge subjected to laser scan (convex and concave sides), Fourier number and laser spot diameter (that controls the laser forming mechanism) on bent angle modification by laser forming of AISI 304 stainless steel blanks. Parameters were varied one at a time. Fourier number and laser spot diameter control the depth and width of plastically deformed region respectively under constant peak surface temperature. While varying Fourier number and laser spot diameter separately the peak surface temperature was kept nearly constant for laser scan on flat samples by choosing appropriate laser power. Laser power was chosen with the help of an analytical model. This is discussed further in Section 2. For a desired surface temperature (that avoids melting and sensitisation of AISI 304 steel blanks) a lower value of Fourier number may be interpreted by a practitioner as choosing a combination of high scan speed and high laser power, which will make the processing time shorter. For materials like austenitic stainless steel AISI 304 temperature rise and cooling rate may also be a concern in thermal processing due to chances of sensitisation. Sensitisation is precipitation of $Cr_{23}C_6$ at the grain boundaries which increases the chances of inter granular corrosion. This occurs for temperature rise in the range of 500–800 °C followed by slow cooling (Singh, 2009). In laser scans however, due to the self-quenching especially under conditions of temperature gradient mechanism the cooling rate is faster. This is beneficial to avoid sensitisation. Nonetheless, peak surface temperature was chosen outside 500–800 °C range to avoid sensitisation at the scan track on top surface exposed to the atmosphere.

2. Laser parameter selection using analytical model

For an infinitely thick sheet subjected to uniform heat flux at the entire top surface as shown in Fig. 1 solution of temperature field can be obtained by solving the following equation:

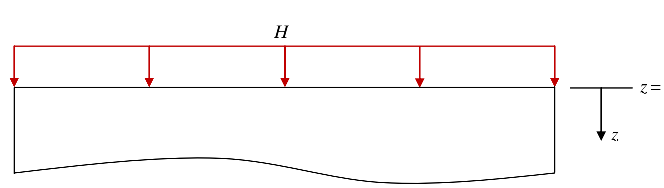

Fig. 1. Schematic representation of an infinitely thick sheet subjected to uniform heat flux at the entire top surface.