EXPERIMENTAL INVESTIGATION ON LASER BENDING OF METAL SHEETS USING PARABOLIC IRRADIATIONS

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Abstract

This paper presents a study on the bending behavior of aluminum sheets during parabolic laser irradiations. Effects of input parameters such as, laser power, scanning speed, sheet thickness and path curvature on bend angle are studied for temperature gradient mechanism (TGM) and buckling mechanism (BM) dominated process conditions. Results showed that the input parameters have non-linear effects on bend angle. The effect of input parameters was found to be different for TGM and BM dominated process conditions. It was observed that for thick sheets, increase in scanning path curvature significantly decreases the bend angle. The deformation behavior of curvilinear laser bending process is different from straight line laser bending. It was observed that in curvilinear laser bending, the workpiece bend outside of the scanning path curvature.

Keywords: Laser bending, curvilinear irradiation, bend angle, path curvature

1. Introduction and literature review

Laser bending is an advanced manufacturing process in which the metal sheet is bent by using thermally induced plastic strains (Li and Yao, 2000). Thermal stresses are induced due to laser beam irradiation over the workpiece surface (Shen and Vollertsen, 2009). These stresses lead to the plastic strains. The process is controlled by various parameters such as laser power, scanning velocity, beam diameter and irradiation path etc. Instead of costly tools, dies or presses, a controlled and concentrated laser beam works as an operational tool to bend the workpiece. Spring back is eliminated in laser bending process which often deteriorates the performance of traditional mechanical bending operation (Kant and Joshi, 2013a). Laser bending is now becoming popular due its advantages such as accurate and easy control over tracking of energy beam on work surface, forming of parts in confined and inaccessible locations, minimal work piece degradation due to smaller heat affected zone, generation of complex shapes, generation of small and accurate bend angles/shapes and bending of brittle materials (Kant and Joshi, 2013b).

The bending behavior of the process can be explained with three mechanisms viz. temperature gradient mechanism (TGM), buckling mechanism (BM) and upsetting mechanism (UM). The dominating mechanism is a result of complex interaction between laser process parameters, workpiece geometry and material properties. In TGM, the bending occurs due to steep temperature gradient along the workpiece thickness. The temperature gradient induces non-uniform thermal stresses which generates corresponding non-uniform thermal strains. Therefore, the deformation is not uniform along the thickness direction and the bending occurs due to difference between plastic deformation at top and bottom surfaces. In this mechanism, the workpiece bends towards the laser source and the bend angle is small (Shi et al., 2006). In BM, the temperature gradient between top and bottom surface is negligible and the bending occurs due to presence of residual stresses, pre-bending or workpiece weight. The bending direction is uncertain and the bend angle is larger in buckling mechanism (Jamil et al., 2011). UM occurs when temperature gradient along the thickness is negligible but geometry of the workpiece is rigid enough to buckle. In that case, instead of workpiece bending, the shortening and thickening takes place in the irradiated region (Shi et al., 2006).

Literature reports experimental and numerical studies on various aspects of straight line laser bending process which includes effect of process parameters (Li and Yao, 2000), edge effect (Bao and Yao, 2001), irradiation strategies (Jamil et al., 2011), multiple irradiations (Edwardson et al., 2006), bending mechanism (Shi et al., 2006), forced cooling
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(Cheng and Yao, 2001) and external mechanical load (Kant and Joshi, 2013a) for wide range of materials. Literature also depicts some work on curvilinear laser bending process to generate complex shapes. Chen et al. (2004) studied the deformation behavior of curvilinear laser bending and found that the deformation occurs only on one side of the scanning path where rigid constraint is lower. Zhang et al. (2007) found that the peak temperature at the scanning surface increases with increase in scanning path curvature. Venkadeshwaran et al. (2010) studied the deformation behavior of circular plate subjected to various patterns of circular laser beam irradiation and stated that pattern of the irradiation affects the quality of the final product. Kant and Joshi (2013b) performed numerical investigation on curvilinear laser bending of magnesium alloy sheet and reported that the bending does not occur over the irradiation path during curvilinear laser bending of sheets. Interestingly, the bending was found to be occurred outside of the scanning path curvature. However, the results were presented based only on the numerical simulation.

From literature review, it was noted that most of the presented work is focused on straight line irradiations. However, the curvilinear irradiation is more convenient to generate 3D complex shapes. Scant literature is reported on the effects of curvilinear irradiation on deformation behavior, temperature distribution and warping of the workpiece. Also, the reported works are mainly focused on the numerical studies. A need thus exists to investigate the effect of scanning path curvature on curvilinear laser bending process. This work is an attempt in this direction. The experimental studies are performed on aluminium sheets to investigate the effect of process parameters and scanning path curvature on TGM and BM dominated curvilinear laser bending process.

2. Experimental details

2.1 Workpiece material and geometry

In the present work, experimental studies were performed on the commercially available aluminium alloy sheet. The composition of material is given in Table 1. The specimen was about 80 mm in length and 50 mm in width. Specimens of two thicknesses 1.45 mm and 0.5 mm were used during experiments.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
<th>Ti</th>
<th>Mn</th>
<th>Cu</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (%)</td>
<td>0.03</td>
<td>97.22</td>
<td>1.65</td>
<td>0.33</td>
<td>0.38</td>
<td>0.35</td>
<td>0.6</td>
</tr>
</tbody>
</table>

2.2 Irradiation strategy

The curvilinear irradiation path chosen was parabolic in nature. It is shown in Fig 1. Equations 1 and 2 represent the parametric equations of parabola.

\[
x = 2at \\
y = 2at \times t
\]

where ‘t’ is the controlling parameter.

Fig 1 shows a parabolic curve with point ‘A’ as the vertex and ‘S’ as the Focus. For parabolic curve, distance ‘SP’ is equal to ‘PM’. The total distance ‘AS’ is denoted as ‘a’. It can be seen that the radius of curvature increases with increase of ‘a’. In this study, seven different values of ‘a’ were considered to study the effect of path curvature.

2.3 Experiment procedure

The experiments were carried out for TGM and BM dominated process conditions. Thin sheets were used for BM whilst thick sheets for TGM dominated laser bending process. Using laser cutting machine, specimens of size 80 mm×50 mm were prepared from aluminum sheet of thickness 0.5 mm and 1.45 mm. The laser cutting was preferred over shear cutting as laser cutting provides dimensionally accurate specimen with no pre-bending and negligible residual stresses. Aluminum have high reflectivity and therefore, to increase the absorptivity, the graphite coating was applied to the specimen prior to the experiments. The coated specimens were allowed to dry under normal room conditions. The experiments were performed on 2.5 kW continuous wave CO₂ laser machine LVD Orion 3015. The specimen was clamped over the laser machine bed using a fixture as shown in Figure 2. The specimens were bent due to laser irradiation and the bend angle was measured using Zeiss make coordinate measuring machine (CMM). The touch probe was moved in x, y and z directions to record the coordinates of the points on either side of the plane. Two points were recorded on both sides of the laser beam irradiation path as shown...
in Figure 3. Two points formed a line and the bend angle was calculated between two lines on both sides of the laser beam irradiation. Figure 4 shows the irradiated specimen. It can be seen that due to laser heating, the coating was burnt out and the workpiece was bent.

![Figure 2 Work holding device with a specimen with curvilinear laser irradiation](image)

![Figure 3 Touch probe of CMM used to measure bend angle of laser bent specimen](image)

![Figure 4 Laser irradiated specimens](image)

3. Results and discussion

The study was carried out on curvilinear laser bending of aluminum alloy. The effect of process parameters on bend angle and deformation behavior are presented for TGM and BM dominated process conditions. The details of the results are discussed below:

3.1 Effect of scanning velocity on bend angle

The aluminum specimens are bent with laser irradiations. The bend angle can be controlled by laser parameters such as laser power and scanning velocity. Fig. 5 shows the effect of scanning speed on bend angle on the sheet of 0.5 mm thickness. It can be observed that the bend angle decreases with increase in scanning velocity. It is because the energy input per unit length decreases with increases in scanning velocity.

![Figure 5 Effect of laser scanning speed on 0.5 mm thin sheet](image)

Fig. 6 shows the effect of scanning speed on bend angle for the sheet thickness of 1.45 mm. It can be observed that for low laser power (300 W), the bend angle is almost constant and thereafter it decreases with increase in scanning velocity. It can be understood by knowing the effects of scanning velocity. The scanning velocity controls the temperature gradient along the specimen thickness and it also controls the energy input into the specimen surface. The temperature gradient increases and energy input decreases with increase in scanning velocity. The bend angle increases with increase in temperature gradient and energy input into the scanning surface. Therefore, the effect of change in scanning velocity is influenced by two parameters one (temperature gradient) increases bend angle and another (energy input) decreases bend angle with increase in scanning velocity. Initially, for laser power of 300 W, both are almost balanced and hence, there is not significant effect of scanning velocity.

For higher laser power of 500 W and 700 W, the bend angle increases with increase in scanning speed. It is because at higher laser power, the peak temperature at bottom surface is high enough to create
plastic deformation. The plastic deformation at bottom surface reduces the bend angle. The increase in scanning velocity results in increase of temperature gradient and hence less plastic deformation at bottom surface. It leads to the increase in bend angle with scanning velocity.

**Figure 6** Effect of laser scanning speed on bend angle on 1.45 mm thick sheet

### 3.2 Effect of laser power on bend angle

Laser power directly controls the energy input in to the workpiece surface. Fig. 7 and Fig. 8 show the effect of laser power on bend angle for sheet thickness of 0.5 mm and 1.45 mm respectively. For sheet thickness of 0.5 mm, the bend angle increases with increase in laser power. It is because of higher energy input due to increase in laser power.

**Figure 7** Effect of laser power on bend angle for 0.5 mm thick aluminum sheet

**Figure 8** Effect of laser power on bend angle for 1.45 mm thick aluminum sheet

The effect of laser power on bend angle for 1.45 mm thick sheet is shown in Figure 8. It can be observed that the bend angle increases with increase in laser power when scanning speed is 4000 mm/min. It is due to combination of higher temperature gradient in the thickness direction at high scanning velocity and more energy input at higher laser power. It leads to the more plastic deformation at top surface and significant temperature gradient (due to high scanning velocity) along the thickness. It leads to the increase in bend angle with laser power.

At low scanning velocity of 1000-2000 mm/min, the bend angle decreases with increase in laser power. It is because aluminum has high thermal conductivity and hence significant temperature gradient cannot be maintained at low scanning velocity. It results in high peak temperature and hence plastic deformation at bottom surface. As laser power increases, the plastic deformation at bottom surface also increases which results in decrease of bend angle. The scanning velocity 3000 mm/min has intermediate effect and the bend angle first increases and then decreases with increase in laser power.

### 3.3 Effect of path curvature on bend angle

Fig. 9 shows the irradiation strategy for studying the effect of path curvature on bend angle. Seven different values of ‘$a$’ were considered for the experiments. It can be seen that as the value of ‘$a$’ increases, the curvature of the parabola decreases and curve tends towards a straight line. The curve will become a straight line for infinite value of ‘$a$’.

**Figure 9** Scheme of parabolic irradiation
Figure 10 Effect of curvature on bend angle for 0.5 mm thin aluminum sheet

Fig. 10 and Fig. 11 show the variation of bend angle with respect to scanning path curvature for sheet thickness of 0.5 mm and 1.45 mm respectively. The curvature is controlled by constant ‘a’. The curvature decreases with increase in the value of ‘a’. Fig. 10 shows that for sheet thickness of 0.5 mm, the bend angle is almost constant with respect to the change in scanning path curvature. This means that the bending of this thin-sheet does not follow the temperature gradient mechanism. Due to low thickness, the bend angle is produced due to buckling mechanism.

Figure 11 Effect of curvature on bend angle for 1.45 mm thick aluminum sheet

For sheet thickness of 1.45 mm, the effect of scanning path curvature on bend angle is shown in Figure 11. It can be observed that the bend angle increases with decrease in scanning path curvature. It may be due to the fact that for longer scanning paths, more energy gets absorbed into the workpiece. This leads to more plastic deformation at bottom surface which reduces the bend angle. For lower lengths of scanning path (lower path curvatures), it is noted that the temperature gradient is lower. This may be due to low pre-heating for shorter scanning lengths. Thus it can be concluded that the bending occurs in these thick sheets is due to the temperature gradient mechanism and the bend angle increases with increase in the value of ‘a’.

3.4 Deformation behavior

In straight line laser bending, the workpiece bends about the irradiation line. In this study, it is observed that the deformation behavior of curvilinear laser bending process is quite different from that of the straight line laser bending process. It is observed that in curvilinear laser bending, the workpiece bending does not occur over the scanning path. It is outside of the scanning path curvature as shown in Figure 12. It shows 0.5 mm thickness laser bent aluminum sheet with curvilinear irradiation. It can be seen that the sheet bending occurs outside of the scanning path curvature near the edges. It may be due to peak temperature offset and tendency of the sheet to bend outside of the scanning path curvature (Kant and Joshi, 2013b). However, at middle of the scanning path, the bending was occurred over the irradiation path.

Figure 12 Bending offset in curvilinear laser bending process

4. Conclusion

In the present work, experimental investigation on curvilinear laser bending of aluminum sheets has been carried out. The effects of various process parameters on bend angle are studied for temperature gradient and buckling mechanism dominated process conditions. The results showed that the bend angle varies non-linearly with laser power and scanning velocity. It was found that the effect of process parameters depends on the combination of process conditions and difficult to generalize. Therefore, there is a need to optimize the process conditions for efficient and quality laser bending process. In thin sheets, the scanning path curvature does not have significant effect on the bend angle however, in thick sheets due to higher temperature gradient, the bend angle increases with decrease in scanning path curvature. The deformation behavior of curvilinear laser bending is found to be different from that of straight line laser bending process. The workpiece is found to be bending outside of the scanning path curvature. The presented results may be useful for complex shape generation using laser micro/macro bending of aluminum alloys.

REFERENCES


