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Original article

Thermo-mechanical studies on bending mechanism, bend angle and edge effect during multi-scan laser bending of magnesium M1A alloy sheets

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ABSTRACT

This paper presents numerical as well as experimental studies carried out to obtain large bend angle (of the order of 10°) in difficult-to-form material, magnesium M1A alloy. Experimental studies were conducted to check the feasibility for bending of material using laser bending process. A finite element based three-dimensional non-linear thermo-mechanical numerical model was developed to simulate the multi-scan laser bending process. The computations provided by the numerical model were validated with experiments; and the validated model was used to investigate the bending mechanism and deformation behavior of the worksheet during multi-scan laser bending process. It was observed that the number of scans has a profound influence on the bending mechanism and deformation behavior. The results showed that the induced thermal stresses decrease and plastic strains increase with number of scans. Edge effect decreases with the increase in number of scans and laser power; whilst it increases with the increase in beam diameter and scan speed. The presented results provide a useful insight into the processing mechanism and will be useful in the selection of suitable process conditions for obtaining large bend angles with minimal edge effect.

1. Introduction

Laser bending is a thermo-mechanical process that uses a defocused laser beam to deform the sheet by means of thermal stresses instead of an external mechanical force. It has many advantages such as accurate and easy control, forming at confined and inaccessible locations, small heat affected zone, generation of complex shapes using suitable scanning strategies, generation of small and accurate bend angles, etc. It has important applications in rapid prototyping, spatial forming, shape correction and alignment of welded components [1]. In laser bending, due to non-uniform thermal and mechanical constraints of worksheets, the bend angle is not uniform along the laser scanning path. This is called edge effect. Laser bending can be explained with three mechanisms *viz.* temperature gradient mechanism (TGM), buckling mechanism (BM) and upsetting mechanism (UM). TGM and BM are responsible for the bending, and UM is responsible for the shortening and thickening of the sheet. The occurrence of dominating mechanism depends on the combination of laser irradiation parameters, sheet geometry and material properties [2].

Literature reports numerical as well as experimental studies on laser bending of a wide range of materials such as steels [3,4], titanium alloys [5], aluminum alloys [6], metal matrix composites [7] and laminated composites [8], etc. Various empirical [9], analytical [10,11], numerical [6,8] and soft-computing [12] models are presented to predict the bend angle and temperature distribution. It was observed that empirical models have limited applicability as they are based on limited experimental data. Analytical models provide fast predictions of process responses, however, the accuracy of these models is not high and typically ranges from 10% to 50%. Moreover, the closed form expressions provide limited information. Soft-computing models are easy to develop and overcome poor predictability of mathematical models. However, these models need training data which can either be collected from experimental results or from existing models. Reliability of soft-computing models depends on the available training datasets and experience of the developer. FEM models provide better accuracy and deeper insight into the process. The FEM simulations offer results in terms of temperature, stress, strain and displacement distributions. Development of FEM based models does not need pre-simulation, experimental or analytical results. Therefore, these

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models are most suitable for the reliable prediction of the process outcomes [13,14].

Most of the reported work on laser bending focusses on single scan laser bending process. Carey et al. [9] investigated the use of laser forming to shape thermosetting glass fiber based metal laminates. It was found that TGM is the only mechanism which gives an out-of-plane bend without a considerable damage to the laminate. Li and Yao [15] studied the effect of strain rate by considering various combinations of laser power and scan speed in such a way that the peak temperature at the irradiated surface remains constant. They found that the bend angle, residual stresses and hardness decrease with the increase in scan speed. Bao and Yao [16] studied the variation in bend angle along the scanning line and found that the bend angle has a concave pattern in the buckling mechanism (BM) and convex pattern in the temperature gradient mechanism (TGM). Guan et al. [17] studied the effect of various thermal and mechanical properties of the sheet material on bend angle. Shi et al. [18] introduced coupling mechanism which is a combination of temperature gradient and upsetting mechanism. Vásquez-Ojeda and Ramos-Grez [19] worked on stepped scanning patterns to obtain a large bend angle using low power laser heat source. Jamil et al. [20] studied the effects of laser beam geometries on buckling mechanism dominated laser bending process. Paramasivan et al. [21] studied temperature distribution and bend angle for laser bending of a plate with rectangular cut and found that the bend angle decreases with the increase in width (along scanning line) of the cut. Paunoiu et al. [22] observed that after melting, the effectiveness of process decreases with the increase in laser power. Kant and Joshi [23] studied curvilinear laser bending of sheets and observed that the bending line differs from the scanning path.

The single scan laser bending produces a small bend angle (of the order of 1°). A larger bend angle can be obtained by incorporating multiple scans which is called multi-scan laser bending process. Cheng and Yao [24] found that the forced cooling can significantly reduce the total forming time in multi-scan laser bending process. They also found that the forced air cooling does not have any adverse effect on the micro-structural and mechanical properties of AISI 1010 stainless steel sheet. Shen et al. [25] investigated two-scan laser bending with different time intervals along the same scanning path. They observed that the plastic deformation is more when the interval between two scans is less. Edwardson et al. [26] reported that the strain hardening, section thickening, change in temperature distribution, variation in absorptivity and change in beam geometry due to the interaction of laser beam with bent worksheet are the influential factors during multi-scan laser bending process. Shi et al. [27] studied various heating methods using multiple scans to reduce the variation in bend angle along the scanning path. Zahrani and Marasi [28] studied the effects of number of scans on edge effect and found that the edge effect decreases with the increase in number of scans. Lambiase et al. [3] studied the effect of passive water cooling to reduce the cooling time between consecutive scans. The passive water cooling was applied by partially immersing the sheet into the stationary water. It was observed that employment of passive water cooling is beneficial in terms of reduction in cooling time, surface oxidation and melting of the irradiated surface.

Incorporation of waiting (interval) time between consecutive scans is essential in multi-scan laser bending. This reduces the surface melting and oxidation of worksheets, however, the increase in waiting time affects the process productivity. Lambiase et al. [29] evaluated the optimal interval time between two consecutive scans at different process conditions during laser bending of stainless steel AISI 304. They introduced a productivity index to evaluate the effectiveness of different process conditions. Productivity index was based on the laser power, scan speed and interval time between two scans. Lambiase et al. [30] developed a neural network to determine the optimal processing conditions that minimizes the processing time. It was observed that the processing conditions that provide maximum bend angle per scan do not necessarily reduce the processing time. Some analytical models are presented to calculate the temperature distribution during laser bending of sheets [31,32]. The presented models help in selecting the interval time between consecutive scans during multi-scan laser bending process.

Most of the reported work on multi-scan laser bending are based on the experimental studies and mainly focus on the productivity of each scan, *i.e.* the bend angle. A scant work has been reported on the effect of process parameters on temperature distribution, stress-strain distribution and distortions during multi-scan laser bending process. Thus, a need was identified to investigate the bending mechanism and the effect of process parameters on the bend angle and edge effect. The present work is an attempt in this direction. Initially, a feasibility study of laser bending of magnesium alloy was carried out. This is presented in the next section.

2. Laser bending of magnesium alloys

Magnesium alloys are widely used in automobile, aviation, aerospace and consumer electronics industries due to their low density, high specific strength, high stiffness, superior damping capacity, high thermal conductivity and good electromagnetic shielding characteristics [33]. They have low ductility at room temperature and therefore difficult to bend with conventional mechanical bending processes.

2.1. Mechanical bending of sheet

The mechanical bending of magnesium alloy worksheet (70 mm length, 40 mm width and 1.9 mm thickness) was carried out to obtain a bend angle of about 17°. The worksheet was bent on a sheet folding machine manufactured by International Machine Tools Corporation, Mumbai (India). Fig. 1 shows a schematic of the arrangement that mechanically bends the worksheet. This system does not have any punch or die arrangement, however, it bends the sheet with less bending radius.

Fig. 2 shows the bent specimen and its magnified microscopic image of the bent region. It was observed that cracks were generated in the bending region. Thus, it can be concluded that the mechanical bending is not suitable for bending of the magnesium alloy sheets.

Palaniswamy et al. [34] reported that due to thermal activation of pyramid sliding planes in the hexagonal closed pack structure, the formability of magnesium alloys increases at an elevated temperature. In view of this, laser bending can be an alternative for crack-free precision bending of the magnesium alloys. Therefore, experiments were conducted to investigate the feasibility of laser bending of magnesium alloys to obtain a significant large bend angle of the order of 10°.

2.2. Laser bending experimental details

In this work, experimental studies on multi-scan laser bending of commercially available magnesium alloy sheet of thickness

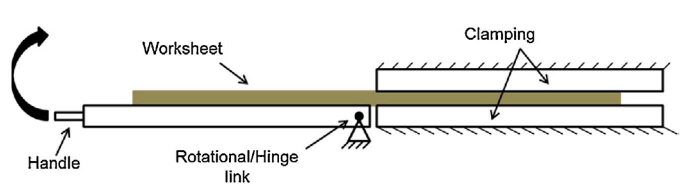

Fig. 1. Schematic of mechanical bending of Mg worksheet.