Process designing for laser forming of circular sheet metal

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Laser forming is a new type of flexible manufacturing process that has become viable for the shaping of metallic components. Process designing of laser forming involves finding a set of process parameters, including laser power, laser scanning paths, and scanning speed, given a prescribed shape. To date, research has focused on process designing for rectangular plates, and only a few studies are presented for axis-symmetric geometries like circular plates. In the present study, process designing for axis-symmetric geometries—with focus on class of shapes—is handled using a formerly proposed distance-based approach. A prescribed shape is achieved for geometries such as quarter-circular and half-circular ring plates. Experimental results verify the applicability of the proposed method for a class of shapes.

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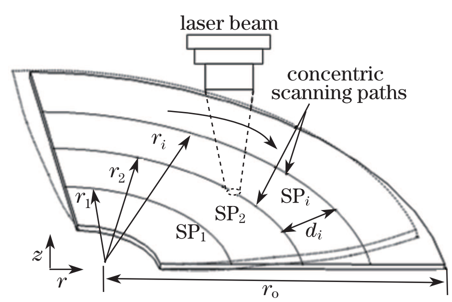
Compared with conventional forming techniques, laser forming of sheet metal does not require hard tooling or external forces. Such advantage can increase process flexibility and reduce the cost of the forming process when low- to medium-production volume is concerned. In recent years, laser-forming techniques have been extensively investigated. In some empirical studies, the relation between a bending angle and process parameters was analyzed[1−3]. However, the results were highly case-dependent. To overcome this shortcoming, a number of finite-element models were developed[4,5]. In Refs. [6,7], simplified relationships between the bending angle and process parameters by analytical models were proposed. Given process and material parameters, a vast majority of work on laser forming can be considered for solving the direct problem, that is, finding the spatial and temporal distribution of temperature, strain/stress state and ultimate deformation of a workpiece. To apply the laser-forming process to real-world problems, however, the inverse problem needs to be addressed, that is, designing process parameters and scanning path planning given a desired shape. Kyrsanidi *et al.* investigated the laser forming of a sine-shaped plate; however, the forming accuracy of the plate was lower due to the equal distance between the scanning paths and the fixed process parameters[8]. Hennige proposed a path strategy for ring and circle segments, but the range of the segment angle was limited[9].

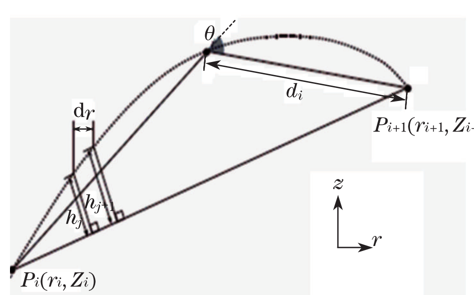
Most of the research to date has focused on laser forming along linear irradiation paths and over rectangular plates. However, to advance the laser-forming process for realistic forming applications in a manufacturing environment, it is necessary to consider process designing for three-dimensional (3D) laser forming for a class of geometrical shapes. To decipher the inverse problem, Kim *et al.* developed two methods: distance-based (DB) and angle-based[10]. However, they implemented those techniques over rectangular plates only. The objective of the present research is to ascertain the applicability of the DB method[10] for non-rectangular simple geometry. This letter is concerned with process designing for a class of shapes, including quarter-circular and half-circular ring plates. As the name depicts, the half-circular ring plate has a total segment angle of 180°, whereas the former has a total segment angle of 90°.

Figure 1 shows a schematic of the laser-forming process for one of the chosen geometries (i.e., quarter-circular ring plate and the procedure of the DB method). It can be seen from Fig. 1(a) that the quarter-circular ring plate is to be formed into a 3D shape by concentric laser scanning paths SP_1, SP_2, $\cdots$, and SP_i. The radii of these scanning paths are r_1, r_2, $\cdots$, and r_i, while d_i shows the radial distance between two successive heating paths.

If the variation of a laser-induced bending angle along an irradiation path is neglected, i.e., edge effects are not considered[11], the 3D shapes can be viewed as shapes generated by a two-dimensional (2D) generatrix[10,12] in the r-z plane revolving around the z axis.



(a)



(b)

Fig. 1. (a) Schematic of the laser-forming process for quarter-circular ring plate; (b) procedure of the DB method.

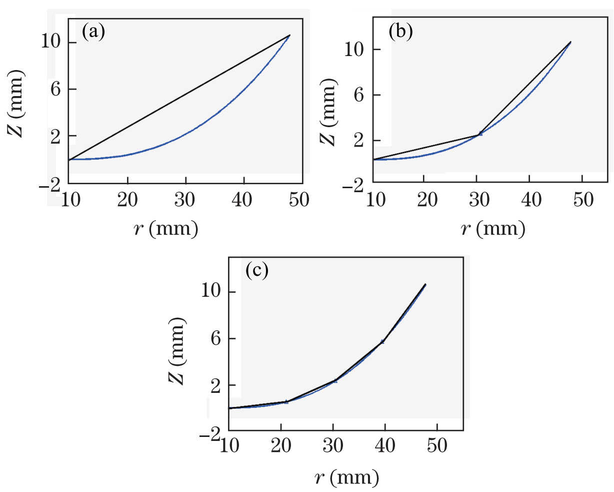


Fig. 2. Results of the DB algorithm. (a) Set start points, (b) first result of making bending points, and (c) the second result of making bending points.

Therefore, for this class of 3D shapes, the inverse design problem can be treated as a 2D curve design problem. Moreover, if the specimen is not so large and the spot size of the laser beam is less than or nearly equal to sheet thickness, then the temperature gradient mechanism (TGM) is dominant enough to acquire a given shape[13,14] and the bending direction is always toward the laser. This study also implies the TGM. For process designing, the parameters need to be determined, including number of scanning paths at distinct position (N), position of laser scanning paths (SP_i), laser power (P_i), beam scanning velocity (V_i), and laser spot diameter, where $i = 1, 2, 3, \cdots, K$. To find the scanning path positions and each bending angle at the path position, a DB algorithm originally proposed by Kim *et al.*[10] is used in this letter.

Using geometrical information, the DB method uses the distance between the target surface and the sheet metal as a criterion for making a new heating point. If the maximum distance between the target shape and the initial sheet metal is larger than the offset distance, the point at the maximum distance is adopted as a new forming point. The procedure shown in Fig. 1(b) of the DB criterion algorithm is as follows:

1) Set offset distance, "h offset" both end points and the contact point as control points, P_i.
2) Start from P_i (r_i, z_i), then calculate h_j. Find a point that has the maximum distance between the target surface and the line from P_i to $P_i + 1$.
3) If the maximum distance is larger than the offset distance "h offset" adopt the maximum distance point as a new forming point.
4) Repeat 2 and 3 until all the maximum distances are smaller than the offset distance.
5) Find d_i, the distance between the forming points and the forming angle θ_i.

Figure 2 shows the procedure of this algorithm for the given shape. After some repetitions, a good result was achieved in making forming points and angles. An optimum value of offset distance needs to be set, which is chosen on the basis of the acceptable error between the target shape and the initial sheet metal. An offset value of 0.05 was used in this study.

Figure 3 reveals the given target shape, heating points found by the DB method, and error in the z direction. The heating points in Fig. 3(b) show the position of respective concentric heating paths. After the irradiation path positions and angles are found, a group of process parameters (i.e., P and V) needs to be determined to bend the plate at the desired angle. There are many possible combinations of these parameters to realize a given bending angle. At this stage, a database needs to be established for the act of furthering the process designing. In a real-world problem, not all the parameters mentioned above have to be determined in the design process; some of them need to be kept constant.

In this letter, quarter-circular and half-circular ring plates of 50-mm outer radius, 10-mm inner radius, and 0.8-mm thickness were used. The material used was low-carbon steel. To enhance laser absorption by the workpiece, graphite coating was applied to the irradiated surface[14,15]. In all experiments, the defocused Gaussian-mode laser beam had powers ranging from 70 to 100 W, while the beam's moving velocity and diameter were 720 mm/min and 1 mm, respectively. Time delay between two consecutive passes was 90 s in the case of multiple number of irradiations (N). A laser displacement sensor was used to measure the bending angle of the deformed plates. Figure 4 shows the result of the database. Figure 4(a) ensures the fact that in case of concentric heating paths, besides others, bending angle also depends on the radius of heating path. This is because of the varying length of heating path along the radial direction,

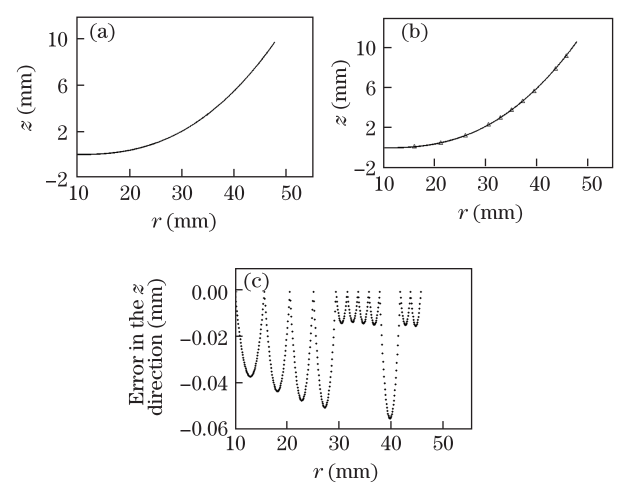


Fig. 3. (a) Target shape; (b) heating points found by the DB method; (c) error in the z direction.

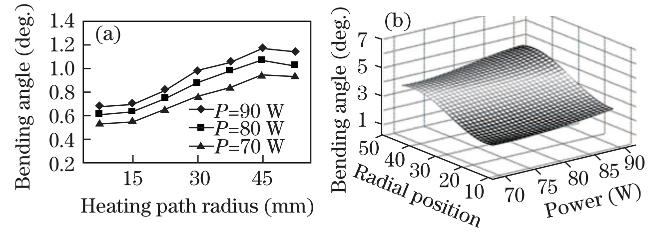


Fig. 4. (a) Relation between path radius and bending angle for quarter-circular ring plate; (b) the third-order fitted surface based on data shown in Fig. 4(a) at $N = 4$.

i.e., curve length[12]. The length of heating path increases with the increase of path radius. Therefore, bending angle increases with increasing path radius (r) up to the path radius of 45 mm. When $r > 45$ mm, the bending angle decreases again because of the encroaching outer edge of the plate. Figure 4(b) shows the database as a result of the third-order fitted surface based on data shown in Fig. 4(a). The relation between the number of irradiations (N), segment angle, and bending angle was found by Nadeem *et al.*[14]. They found that, with the same parameters, there is a minor variation of total deformation between quarter-circular and half-circular ring plates. This eliminates the requirement for individual experiments for each plate. Therefore, the database found for the quarter-circular ring plate was also used for the half-circular ring plate.

The general shape of the resultant laser forming was similar to the target shape. However, an error existed in the results with a spread of around ±15% at each single bending angle, which is similar to the result of earlier research[10,16].

After determining the heating points and corresponding bending angles by the DB method (Table 1), the established database (shown in Fig. 4) is used to select the remaining process parameters. For the corresponding bending angle, appropriate power is chosen with respect to the path radius that deforms the plate at the required profile. Typical samples of formed plates and measurements of the surface profile are shown in Figs. 5 and 6, respectively. The error shown in Fig. 7 is within acceptable limits; however, for high precision, this error needs to be eliminated.

In conclusion, the inverse problem for circular sheet metal is analyzed and solved by a geometrical approach. The applicability of the DB algorithm for non-rectangular plate is verified. Target shape for the

Table 1. Distance between Scanning Paths (d_i), Radius of Scanning Paths (r_i), and Each Forming Angle (θ_i) Computed by the DB Method

No.	d_i (mm)	r_i (mm)	θ_i (deg.)
1	5.21	15.21	3.37
2	4.85	20.07	4.19
3	4.72	24.79	4.66
4	2.40	27.20	3.69
5	2.33	29.53	2.50
6	2.37	31.90	2.49
7	2.41	34.32	2.50
8	4.75	39.08	3.64
9	2.46	41.54	3.51
10	2.52	44.07	2.30
	Total Length=50.074		

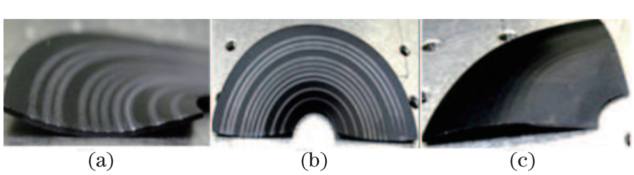


Fig. 5. Results of experiments (a) and (b) for the half-circular ring plate and (c) for the quarter-circular ring plate.

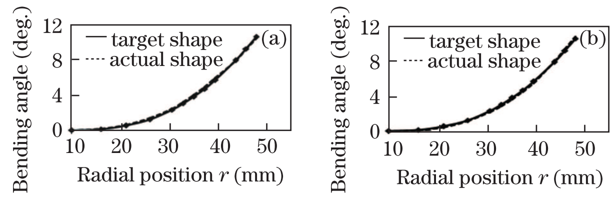


Fig. 6. Measurement of target shape. (a) Quarter-circular ring plate and (b) half-circular ring plate.

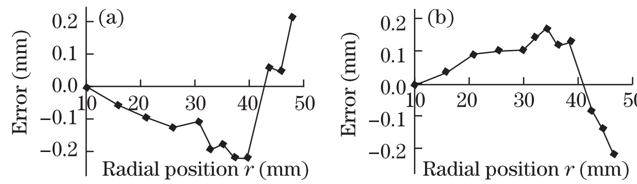


Fig. 7. Error between target shape and actual shape after experiments. (a) Quarter-circular ring plate and (b) half-circular ring plate.

quarter-circular and half-circular ring plates is achieved within acceptable error. The accuracy of the results is adjusted freely by changing the offset value of the algorithms. Moreover, in case of curved irradiations, experiments show that the bending angle increases with increasing value of path radius until influenced by edge effects. Axis-symmetric circular shape is easily handled by considering the target shape as a 2D curve generatrix. This means that the procedure might have a potential for other classes of shapes. Future work will focus on handling the inverse problem for more complex classes of shapes.

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