Numerical Investigation of Laser Bending of Perforated Sheets

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Abstract: In this work, laser bending of perforated sheets has been investigated numerically. Laser bending of perforated sheets is more complicated than non-perforated sheets due to their complex geometries. In this paper, laser bending of perforated sheets is studied numerically in the form of thermo-mechanical analysis with ABAQUS/IMPLICIT code. For this purpose, the effects of process and sheet parameters such as laser output power, laser scanning speed, laser beam diameter and the number of punches in the sheet are investigated on the bending angle of laser formed perforated sheet. The results show that the larger punch diameters lead to decrease in bending angle in the laser formed perforated sheets. Also, it is concluded that the bending angle of the perforated sheet is decreased with increasing laser scanning speed. In addition, bending angle is decreased with decreasing laser beam diameter.

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1   INTRODUCTION

Laser forming recently has emerged as a new shaping technique that offers excellent reproducibility, low manufacturing time and cost, as well as, relatively low thermal influence on the material mechanical properties. For those reasons, laser forming is a promising technique with several potential applications in the automobile, shipbuilding and in particular aerospace industry, where the demand to form integrally stiffened structures is high. In comparison to conventionalforming technologies, LBF provides the potential for many technological advantages, especially in cases of forming complex or semi-assembled structures of various thicknesses and material types, as well as in rapid prototyping applications. The laser forming technique has been extensively investigated during the recent years. Numerical and experimental investigations have been carried out to better comprehend the mechanisms and the effects of the control parameters on, for example, bending angle and mechanical behaviour.

The improvement in computational efficiency in recent years has made thermo-mechanical numerical studies more viable. With the release of more user friendly numerical modelling software packages such as ANSYS and ABAQUS coupled with faster computers, the use of numerical models as a research tool for both academic and industrial sectors is becoming more prevalent. In recent years, many researchers have investigated laser forming of simple (non-perforated) sheets numerically.

In 2002, Chen et al., [1] established a computational model of temperature field on the basis of the non-Fourier heat transfer equation, with taken into account the effect of rate of heat transfer on temperature distribution. In their work, the influence of the time step size on the computed results was discussed. More recently, Shen et al., [2] presented a finite element analysis model for the heat transfer problem of laser forming of the plates. The results showed that the influence of the heat exchange through radiation on boundaries on the temperature distribution can be negligible.

In 1993, Vollertsen et al., [3] developed a finite difference model for a two dimensional (2D) analysis of the process. The temperature dependent material parameters were included in the model by taking values at particular temperatures and linearly interpolating between them, and then those functions were used to relate the temperature to the material properties. This model provided a very fast means of calculating the effects of various process parameters, but the simple boundary conditions that limited this approach led to the modelling with the finite element method (FEM). Meanwhile, Alberti et al., [4] used FEM to model the

TGM to evaluate the temperature field and then the results of this analysis were input into a mechanical analysis. A constant decay law was assumed for the relationship between increasing temperature and decreasing yield stress.

Another numerical simulation was developed by the same authors [5] in examining the combined process of thermal and mechanical bending. Hsiao et al., [6] used the commercial package ABAQUS to model the process. They used the model in their work to emphasize the importance of the specimen size. Their results showed that the angular distortion obtained on a short specimen is much smaller than for a long specimen. In work done by Holzer et al., [7], the BM was modelled using the commercial finite element package ABAQUS. A user defined FORTRAN function was used to model the heat input from a non-uniform heat flux.

In 2001, Li and Yao [8] proposed a new scanning scheme in which laser scanning starts from a location near the middle of the work-piece instead of normally from an edge of the work-piece. Using this scanning scheme, convex forming is realized with high certainty under the BM conditions, unlike the case of scanning from the edge. Hu et al., [9] performed a three dimensional (3D) FEM simulation that included a non-linear, transient, indirect coupled, thermal–structural analysis accounting for the geometric and material nonlinear properties. The buckling deformation, bending angle and distribution of stress–strain and temperature, as well as residual stresses, were obtained from the simulations.

In 1997, Magee et al., [10] discovered the edge effects phenomenon in laser forming experiment. Then Bao and Yao [11] studied the edge effects using FEM under both BM and TGM. The results showed that edge effects are characterized by a concave pattern in the bending angle variation along the scanning path under BM and a convex bending angle variation under TGM.

In 2007, Shen et al., [12] presented a numerical study on the edge effects of laser bending using varying scan speed. Because the laser forming process analyses are time dependent, the finite element analysis model involves the discretisation in space and in time. The variation of the scan velocity thus can be implemented in the program by specifying the dwell times on corresponding elements. Later, they [13] proposed a total of seven varying velocity scanning schemes to reduce the edge effects, and the results showed that the combination of acceleration and deceleration scanning scheme can minimize the edge effects.

In 2013, Safari et al., [14] investigated the laser bending of tailor machined blanks experimentally and numerically. Their results showed that the laser bending process of tailor machined blanks was more complicated than monolithic plates. In their work, a

new irradiating scheme for laser bending of tailor machined blanks was proposed. Using this irradiating method, the differences in bending angles in various sections of tailor machined blanks and also multi-curvature bending phenomenon was extremely reduced. Also, in 2013, Safari et al., [15] investigated the effects of process parameters on benging angle of laser fomed tailor machined blanks. The start point of scan path, irradiating method, laser output power, beam diameter and number of radiation passes were considered in the evaluations.

The results showed that irradiating method, laser output power, beam diameter, number of radiation passes and start point of scan path had the most importance effects on bending angle respectively. In 2014, Safari et al., [16] studied various irradiating schemes for laser bending of tailor machined blanks. For this purpose, three different irradiating schemes i.e. variable speed method (VSM), variable power method (VPM) and variable beam diameter method (VBDM) were considered. Their results showed that VSM was a better irradiating scheme than VPM and VBDM for laser bending of tailor machined blanks. After VSM, the VPM was a suitable choice. It was also concluded that VBDM was not a suitable method for laser bending of tailor machined blanks in comparison with VPM and VSM. As it was seen in the literatures, all of previous investigations have been focused of laser forming of non-perforated sheets and to the author's knowledge, there is no reported research on laser bending of perforated sheets.

In this work, laser bending of perforated sheets has been investigated numerically. Due to complex geometries of perforated sheets, laser bending of perforated sheets is more complicated than non-perforated sheets. Numerical investigations are performed using ABAQUS/Implicit code. The effects of process and sheet parameters such as laser output power, laser scanning speed, laser beam diameter and the number of punches in the sheet are investigated on the bending angle of laser formed perforated sheets.

2　NUMERICAL WORK

As the laser bending is a thermo-mechanical process, its computer simulation is more complicated than other manufacturing processes. In the numerical simulation of laser bending process many factors should be considered such as heat flux due to laser irradiating, temperature change during the process, material property changes and the effect of thermal strain on sheet characteristics. In this study, laser bending process of perforated sheets is simulated using ABAQUS/ Implicit code. In the following some points

that should be considered in thermal and mechanical analysis are noted.

- The surface heat flux distribution is computed according to Gaussian distribution.
- Boundary heat transfer is modeled by natural heat convection and radiation.
- Heat generated due to phase change is neglected.

The governing equation of the hat conduction can be expressed as follow [17]:

$$\rho c \frac{\partial T}{\partial t} = \nabla \left(k \nabla T \right) \tag{1}$$

Where ρ is material density (kg/m3), C is the specific heat (J/kg ˚C), T is the temperature (˚C), t is the time (s), k is the thermal conductivity (W/m˚C) and ∇ is the gradient operator.

It should be noted that in the present study x and y axes are in the plane and z axis in perpendicular to the plane. In the laser bending simulations, laser beam should be considered as a moving heat source. The moving heat flux generated by the laser beam is assumed to have a Gaussian distribution which is on the top surface of the plate as follow [17]:

$$I(x,y) = \frac{2AP}{\pi R^2} \exp \left(-\frac{2(x - vt)^2 + (y - y_0)^2}{R^2} \right) \tag{2}$$

where $I(x,y)$ is the thermal flux density of the laser beam at the point (x,y) (W/m^2), A is the absorptivity on the steel plate surface, P is the laser beam power (W), R is the laser beam radius (m), v is the scanning velocity, $x_0 = vt$ and y_0 are the center of the laser beam (m).

The heart transfer analysis is time-dependent. However, the time scale required for heat conduction is much longer than that required for structural vibration. Therefore, as far as the stress analysis is concerned, it can be regarded as a quasi-static analysis, that is, the inertia and damping forces can be ignored during the stress analysis phase although the solutions are still time-dependent because the thermal strain varies with temperature and thus with the time. For boundary condition in mechanical analysis, necessary constraints are added to eliminate rigid body movement.

The samples were made from carbon steel ST37 with 100mm (length) $\times$ 50mm (width) $\times$ 1mm (thickness). In Fig. 1, a schematic view of the initial perforated sheet is shown. According to laser forming process of perforated sheets, necessary boundary conditions must be applied on model in the mechanical and thermal analysis.
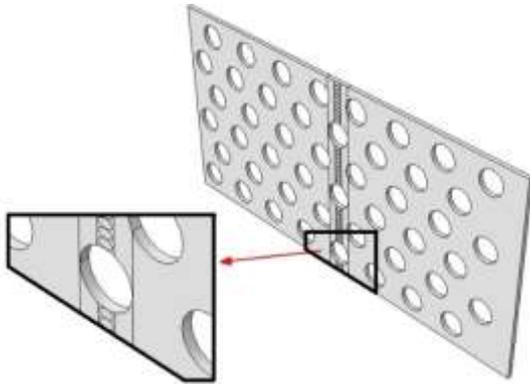
Fig. 1   A schematic view of initial perforated sheet

In order to prevent rigid body motion in thermo mechanical coupling analysis, displacements and rotations of one side of perforated sheet are constrained. Thermal boundary conditions in the form of convention and radiation are applied to sheet surfaces. Convection thermal boundary condition is based on Newton's law and expressed as [15]:

$$q = h_c \left(T_S - T \right) \tag{3}$$

In equation 3, h_c is convection coefficient, T_S is the sheet surface temperature and T is the ambient temperature. Radiation thermal boundary condition is as follows [15]:

$$Q = 5.67 \times 10^{-8} \varepsilon \left(T_S^4 - T^4 \right) \tag{4}$$
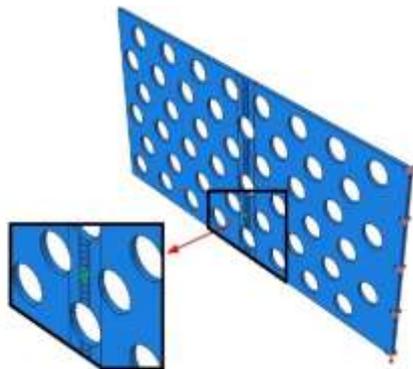
Fig. 2   Mechanical constraints in the laser forming of perforated sheet

In equation 4, ε is the sheet surface emissivity, T_S is the sheet surface temperature and T is the ambient temperature. In order to maintain laser beam motion effect continuity, the temperature differences should not exceed more than 20˚C in each time increment.

Continuous moving heat source is implemented in the ABAQUS using DFLUX subroutine written in FORTRAN language. Figure 2 exhibits how the mechanical constraints are applied in the laser forming process of perforated sheets.

In ABAQUS software, C3D8T element (3D continuous eight point element of thermo mechanical coupling) is used for themo-mechanical soulotion of laser forming of perforated sheet. Figure 3 presents employed mesh pattern for perforated sheet in the numerical simulations.
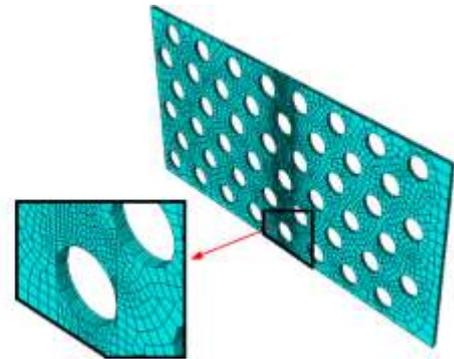
Fig. 3   Mesh pattern in the perforated sheet

3   RESULT AND DISCUSSIONS

3.1. Temperature distribution and displacement contours of the laser formed perforated sheet

Figs. 4 and 5 depict temperature and deformation contours in different times for a perforated sheet that is irradiated with a laser beam. For obtaining this result, laser output power, laser scanning speed, laser beam diameter and the number of scan passes have been adjusted as 120W, 2 mm/s, 1.5 mm and 1 pass, respectively. As it is seen in Fig. 4, maximum temperature of the workpiece is attained at the center of the laser beam.

In the following the effects of various process parameters on obtained bending angle in the laser bending of a perforated sheet are investigated.

### 3.2. Effect of punch diameter on bending angle

The diameter of punch of a perforated sheet is a significant parameter that can particularly affect the bending angle in laser bending of these sheets. Thus, in this section the effect of this factor in three different diameters such as 4, 6 and 8 mm is investigated. Figure 6 illustrates the effect of variation in laser power in the perforated sheets with different punch diameters. According to this figure, larger punch diameters lead to decrease in bending angle in the laser formed perforated sheets, because increasing the punch diameter of the perforated sheet, amount of materials of

the perforated sheets is decreased and more heat fluxes are dissipated in the laser bending process.


(a)

(b)

(c)
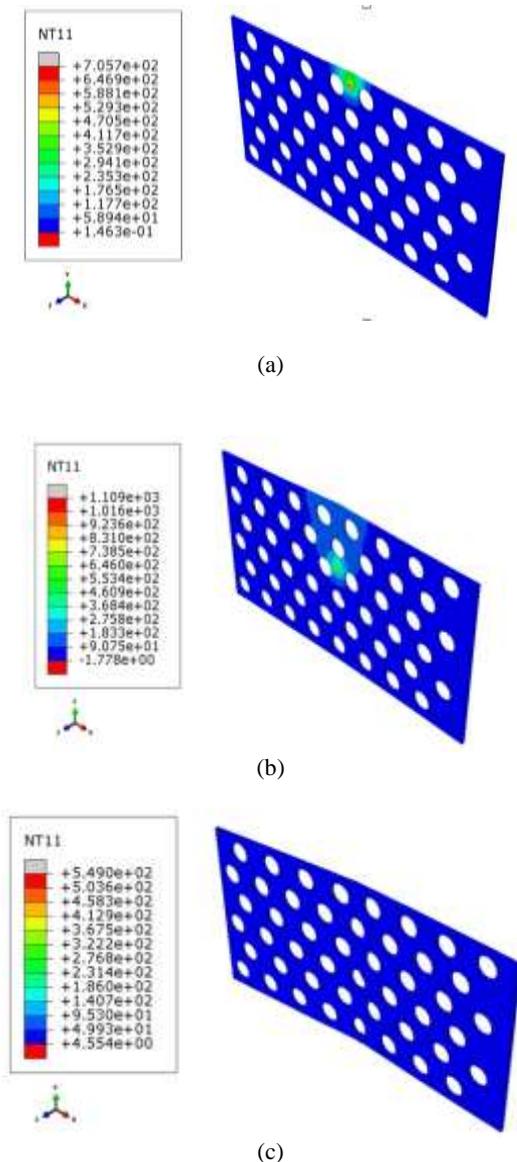
Fig. 4   Temperature distribution in the perforated sheet at various times of laser bending process, a- 1.5 seconds, b- 9.5 seconds, c- after cooling

Whereas, upward trend in bending angle with an increase in laser power is still remained. The reason is that with increasing the laser power, induced heat flux into the plate increases and therefore plastic deformation areas in the plate are increased. The results of variation in laser scanning speed and laser beam diameter in laser forming of perforated sheets with various punch diameters are presented in Figs. 7 and 8.


(a)

(b)

(c)
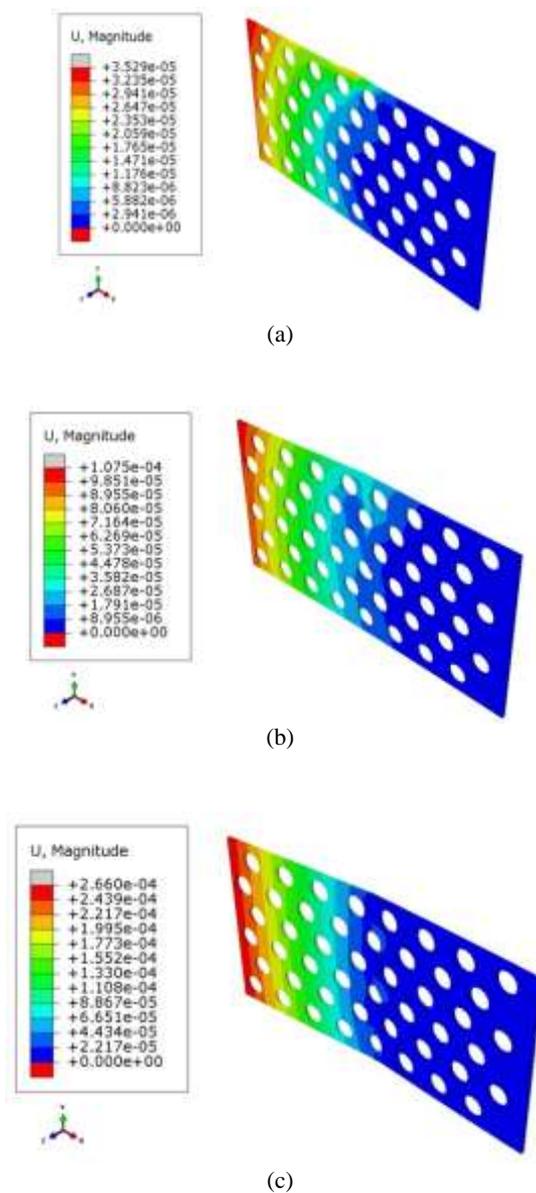
Fig. 5   Deformation contours in the perforated sheet at various times of laser bending process, a- 1.5 seconds, b- 9.5 seconds, c- after cooling

According to these figures, it can be observed that the bending angle decreases with an increase in punch diameter of perforated sheet. However, the general trends of variations in bending angles of perforated sheet are the same. As it is seen in Fig. 7, with increasing laser scanning speed, the bending angle of laser formed perforated sheet is decreased.

The reason is that with increasing the laser scanning speed, there is not sufficient time for inducing the heat flux into the plate and therefore plastic deformation areas in the plate are decreased.
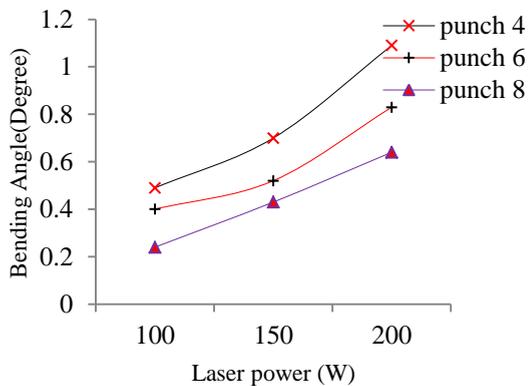
Fig. 6 Effect of laser beam power on the bending angle with various punch diameters, laser scanning speed= 2 mm/s and laser beam diameter = 2 mm
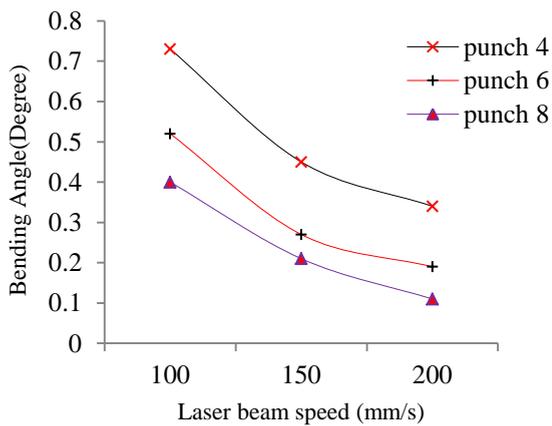
Fig. 7 Effect of laser beam speed on the bending angle with various punch diameters, laser power= 150 W and laser beam diameter = 2 mm
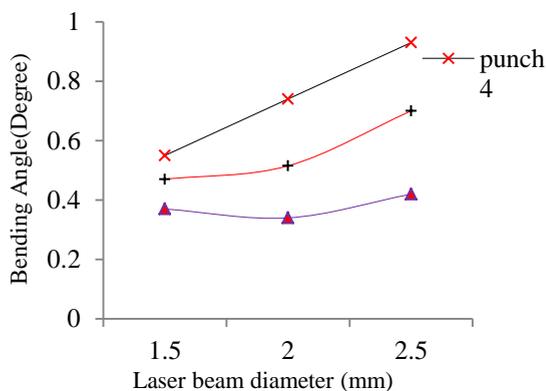

Fig. 8 Effect of laser beam diameter on the bending angle with various punch diameters, laser power = 150 W and laser scanning speed= 2 mm/s

It is concluded from Fig. 8, with increasing the laser beam diameter, resulted bending angle of perforated sheet is increased.

3.3. Effect of number of punches on bending angle of laser formed perforated sheet

In this section, the effect of number of punches on bending angle of perforated sheets is investigated in different conditions. In these investigations, the punch diameter is 5 mm and the number of punches in the laser irradiating path is 3, 4 and 5 punches. Fig. 9 represents the effect of laser power on bending angle of perforated sheets with different number of punches in the laser irradiating path. As it is seen in this figure, the bending angle of perforated sheet is decreased with increasing the number of punches in all examined powers.
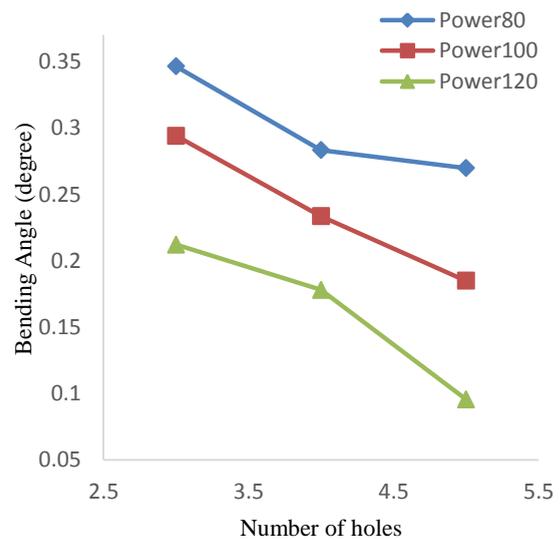
Fig. 9 Effect of laser power on bending angle of perforated sheet with different number of punches

The reason is that with increasing the number of punches, the length of areas of perforated sheet which has been exposed to laser beam is decreased. In other words, the length of areas of perforated sheet which has been subjected to temperature gradient will decrease with an increase in the number of punches. Therefore, lower bending angles in the perforated sheets are obtained with increase in the number of punches. Also, it can be seen from Fig. 9 that the drop percentage in the bending angle is much greater in higher powers; that is because the temperature gradient and its effects are more influential in the higher powers.

In the following, the effect of different laser scanning speeds is studied in the laser bending of perforated sheets with different number of punches. For this purpose, perforated sheets with 3, 4, and 5 punches

along the laser irradiating path are laser formed with various scanning speeds such as 2, 3 and 4 mm/s. Fig. 10 represents variation of the bending angle for different scanning speeds in the perforated sheets with different number of punches along the laser irradiating path. As it is seen in this figure, an increase in the number of punches of perforated sheets leads to a drop in the bending angle in the entire laser scanning speeds. This trend is almost linear in the scanning speed of 2 mm/s and is non-linear in the higher scanning speeds.
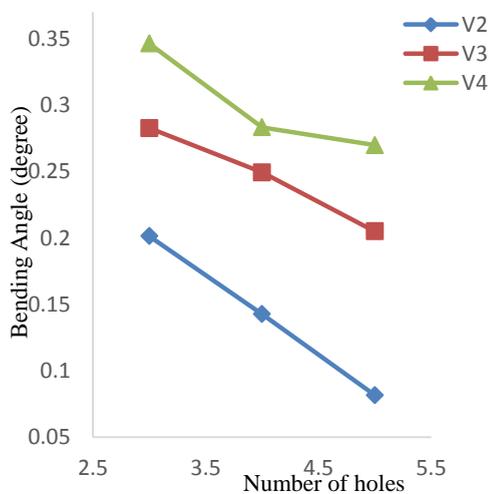

Fig. 10   Effect of laser scanning speed on bending angle of perforated sheet with different number of punches
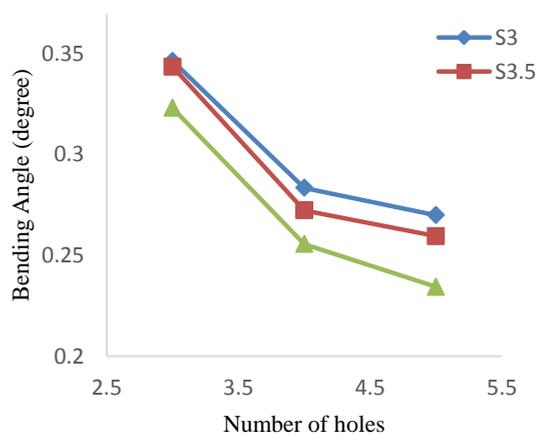

Fig. 11   Effect of laser beam diameter on bending angle of perforated sheet with different number of punches

Also, in Fig. 11 the effect of laser beam diameter on the bending angle of perforated sheets with different

numbers of punches along the laser irradiating path is shown. For this purpose, the perforated sheets were subjected to laser beam with different beam diameters including 3, 3.5, and 4 mm. These results show that the bending angle is decreased in all laser beam diameters with an increase in the number of punches of perforated sheet. According to this figure, bending angle in the perforated sheets for laser beam diameters of 3 and 3.5 mm are nearly the same.

4   CONCLUSION

In this paper, laser bending process of a perforated sheet was investigated. The effects of process and sheet parameters such as laser output power, laser scanning speed, laser beam diameter and the number of sheet punches on the bending angle were investigated. Laser bending of perforated sheets was studied numerically in the form of thermo-mechanical analysis with ABAQUS/IMPLICIT code. Following results were obtained as follows:

- Larger punch diameters lead to decrease in bending angle in the laser formed perforated sheets. Whereas, upward trend in bending angle with an increase in laser power is still remained.
- It is concluded that the bending angle of the plate is decreased with increase in the laser scanning speed. The reason is that with increasing the scan speed, there is not sufficient time for inducing the heat flux into the plate and therefore plastic deformation areas in the plate are decreased.
- It is observed that resulted bending angle of the plate is increased with increasing the beam diameter.
- The bending angle of perforated sheet is decreased with increasing the number of punches in all examined powers. The reason is that with increasing the number of punches, the length of perforated sheet which has been exposed to laser beam is decreased.
- The results show that the increase in the number of punches of perforated sheets leads to a drop in the bending angle in all of laser scanning speeds.
- These results show that the bending angle will decrease in all laser beam diameters with an increase in the number of punches in the perforated sheet.

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