The Effect of Laser Power and Laser Scan Passes on Bending Angle of Stainless Steel AISI 304 Laser Bending

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Abstract. The application of laser bending of thin sheet metal are quite limited given that this forming process is widely used in various industries. The aim of this paper is to study the effect of laser power and laser scan passes on bending angle of stainless steel AISI 304 lasers bending. This study considers using parametric combinations of laser power and laser scan passes (number of loops) as the laser bending process parameters. The corresponding effects of these process parameters on bending angle of stainless-steel thin sheet metal (t=0.1mm) was observed. The results obtained shows that the bending angle increased with increased in laser power and laser scan passes, meaning that these parameters does significantly affect the bending angle. Other than bending angle, there were also a few bulges observed at certain location along the laser scan path for certain parametric combination of process parameters tested.

Keywords: Laser Bending, Laser Power, Laser Scan Passes, Bending Angle, Stainless Steel.

1. Introduction

Laser bending is a contactless process for sheet bending of ductile metals, in which a laser beam heats specific zones of material, generating thermal stresses that exceed its yield strength and inducing plastic deformation that finally bends the metallic sheet [1]. The unexpected increase of research reported on this topic in recent literature demonstrates the clear promise of laser-based techniques in processing metals. [2]. In thin sheets metal forming, laser is a better option [3]. Changdar & Chakraborty [2] in 2021 stated in their recent review article that the advantages of laser bending forming are its flexibility, the lack of need for hard tooling, and the ability to form both hard and brittle materials.

In general, there has been many research done regarding the application of multiple laser scan bending or forming on sheet metal. In 2021, Shi et al. [4] used a low heating temperature to investigate laser thermal bending under pre-load and discovered that multiple scanning of a low-temperature laser improves surface quality while also allowing for a larger bending angle. Another attempt by Thomsen et al. [5] in was also done in 2020 to study the rate of change in bending angles has led to a hypothesis that the thermal expanded area is limited not only by the surrounding material, but also by deformation caused by the laser-formed part of the laser scan path. Due to the additional forces restricting the thermal expansion, this could result in a larger total bend angle. Since these effects do not occur at the laser scan path's trailing edge, another possibility is changes in bending angle along the laser scan path. However, Thomsen et al. [5] (2020) stated that this hypothesis requires additional research before anything can be concluded.

Other than these experimental research done, there was a prediction model and experimental validation done by Mulay et al. [6] in 2021 regarding the bending angle on multiple laser scan passes on 304 stainless steel. They consider the temperature dependent properties of the sheet material to evaluate the temperature profile across the thickness of the sheet. They conclude that the variation in the bend angle per laser scan for 304 stainless steel sheets processed with different laser parameters was found to depend laser power and scanning speed, the key parameters affecting the results of multi-scan laser forming.

In this paper, the aim is to study the effect of laser power and laser scan passes on the bending angle of the stainless-steel thin sheet metal with the thickness of 0.1mm. What made this paper important is that this study was done using a very thin sheet metal and using low power fibre laser machine, as there are not many studies regarding this, according to our findings. At the end of the experiment, the size of the bending angle was observed and the images were captured to compare the differences of bending angle in regards to the process parameters tested. The results were also tabulated in graph plot to observe the significant effect of these process parameters on final bending angle and average bending angle.

2. Experimental Procedures

2.1 Material and Sample Preparation

AISI 304 stainless steel thin sheet of 40 × 10 × 0.1 mm was used in this study. Three samples of each parametric combination were prepared keeping the sheets orientation for all samples are the same as to avoid any effects of sheet anisotropy. The samples were cut using a cutter and cleaned using acetone to remove any grease of oil that might affect the heat transfer. The sheet has a chemical composition of Fe (68%), Cr (19%), Ni (9%), Mn (2%), C (0.08% max), P (0.045% max), Si (1% max).

2.2 Experimental Setup

The low laser power tests were conducted using a fiber laser (IPG YLM 200/2000) with a maximum power of 27 W and wavelength of 1070 nm. See Fig. 1 which shows the schematic diagram of sample workpiece with clamping jig. A simple jig clamp was used to fix the sample workpiece 20mm from one end and free the other end. The laser scan line with the length of 14mm was performed across the workpiece 10mm from the free end of the workpiece. A continuous mode operated laser beam with the beam diameter of 50µm was irradiated over the top sheet surface along the sheet width to complete one laser scan. Different combination of laser scan passes (4, 8, 12, 16 and 20 loops) and laser power (21, 24 and 27 in Watts) were tested with constant scanning speeds of 41.67mm/s and the focal length of 132mm, as shown in Table 1.

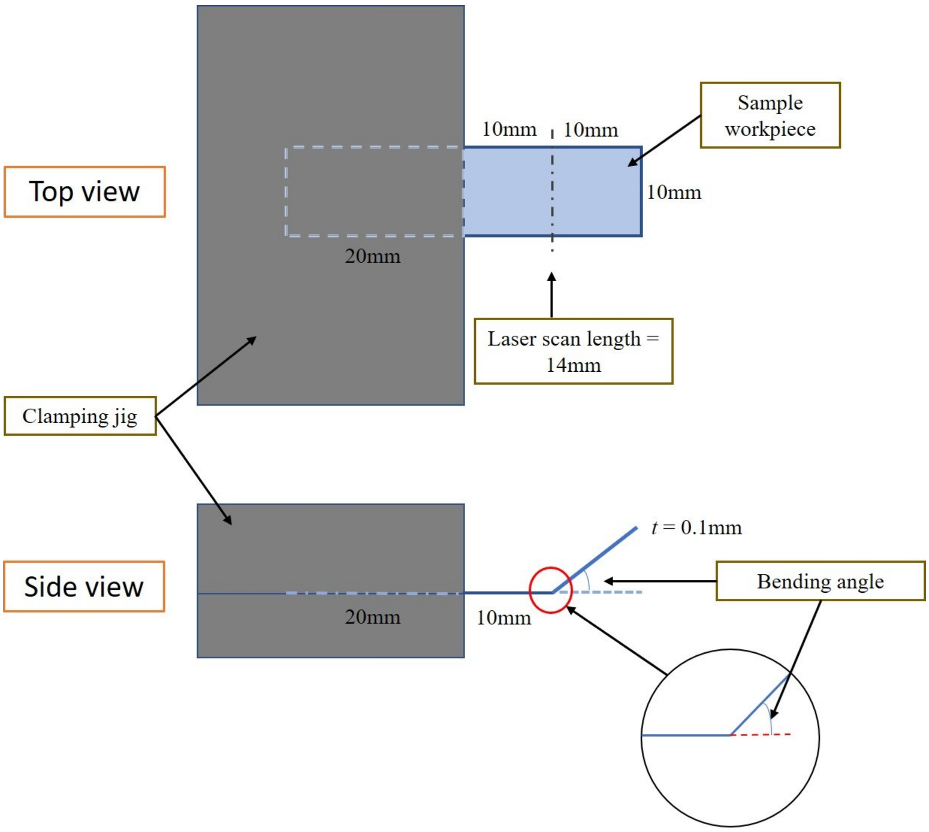


Fig. 1. Schematic diagram of jig clamp and sample workpiece.

Table 1. Laser process parameters used in this study.

Parameters	Variations
Laser Power (W)	21, 24, 27
Laser Scan Passes	4, 8, 12, 16, 20
Laser Speed (mm/s)	41.67
Focus Length (mm)	132

3. Results & Discussion

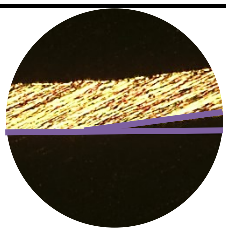
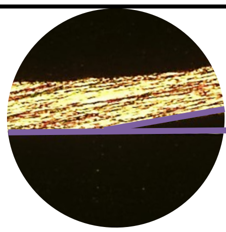
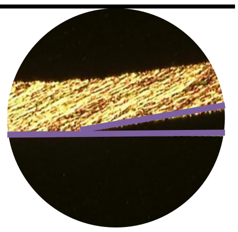
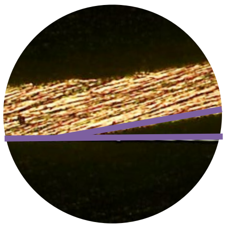
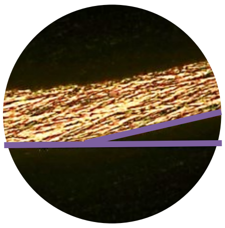
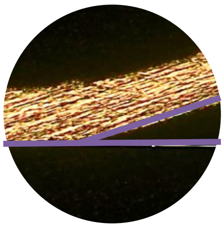
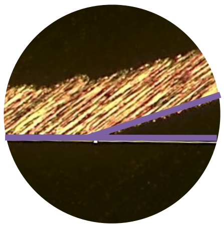
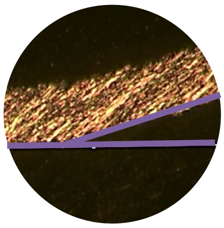
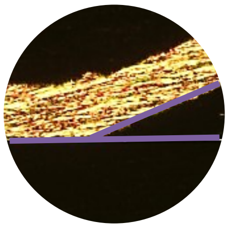
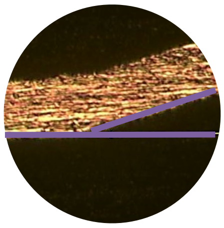
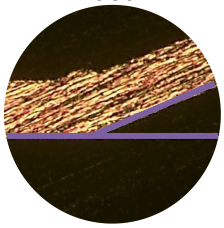
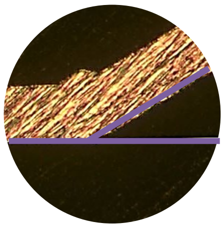
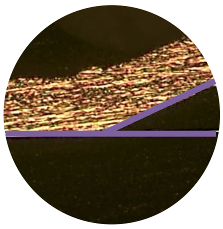
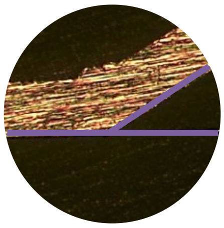
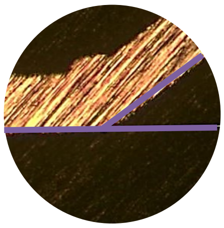
The final bending angle results for all laser parametric combination were shown in Table 2, and. Table 3 below presents the changes in bending angle in close-up images for each parametric combination of 3 different laser powers and 5 different laser scan passes (loops). The laser scan passes were performed along the same laser irradiation track for 5 different loops. On the 4th loop test, there were only small changes of the bending angle from 21 W to 27 W laser powers tested with the difference of 1.19º. On the 16th loop, there were quite big changes in bending angle for 24 W and 27 W laser powers with the difference of 7.518º among others. From 12th to 20th loops, there were large changes in bending angle occurred with different laser powers. As seen in the images below, the bending of the workpiece was observed to be quite uniform for both constant laser power and laser scan passes. It can also be seen that increasing in laser power promotes larger bending angle. Also, as the laser scan passes overlapped on the laser irradiation track for multiple times, the bending angle also becomes larger.

Other than bending, we also noticed in the images that there is a bulge formed on top of the sample workpiece on the bending area at 27 W laser power at 8th loops. There were also bulges occurred at the parametric combination of 12th loops at 24 W and 27 W, of 16th loops at 24 W and 27 W and of 20th loops at 21 W, 24 W and 27 W laser powers. These buckles formed as a result of thermal compressive stresses developing in the sheet during laser beam heating, resulting in a considerable amount of thermo-elastic strain and local thermo-elastic-plastic buckling of the material [7]. This buckle is created by the laser beam scanning moving in the same direction. The buckle is formed on top of the sample workpiece surface when the laser beam departs it. The buckle occurs is uncertain shapes and locations and it is largely depending on the initial stress/strain state and the surface condition of the sample workpiece. As for this study, the bulges do not form along the laser scan line, rather it only formed on certain locations with different sizes of bulges. Hence, the bulges cannot be measured accurately.

Table 2. Final bending angle for each parametric combinations tested.

Final Bending Angle (º)		Laser Scan Passes				
		4	8	12	16	20
Laser Power (W)	21	8.973	12.914	18.476	19.006	24.656
	24	9.557	13.776	18.083	22.577	31.645
	27	10.433	18.058	25.333	29.833	36.742

Table 3. Close up images of final bending angle formed.

Laser Power (W) / Laser Scan Passes	21	24	27
4	 5.884º	 7.074º	 8.618º
8	 9.869º	 12.177º	 17.151º
12	 15.62º	 18.38º	 23.244º
16	 17.79º	 22.116º	 30.634º
20	 24.32º	 30.547º	 36.305º

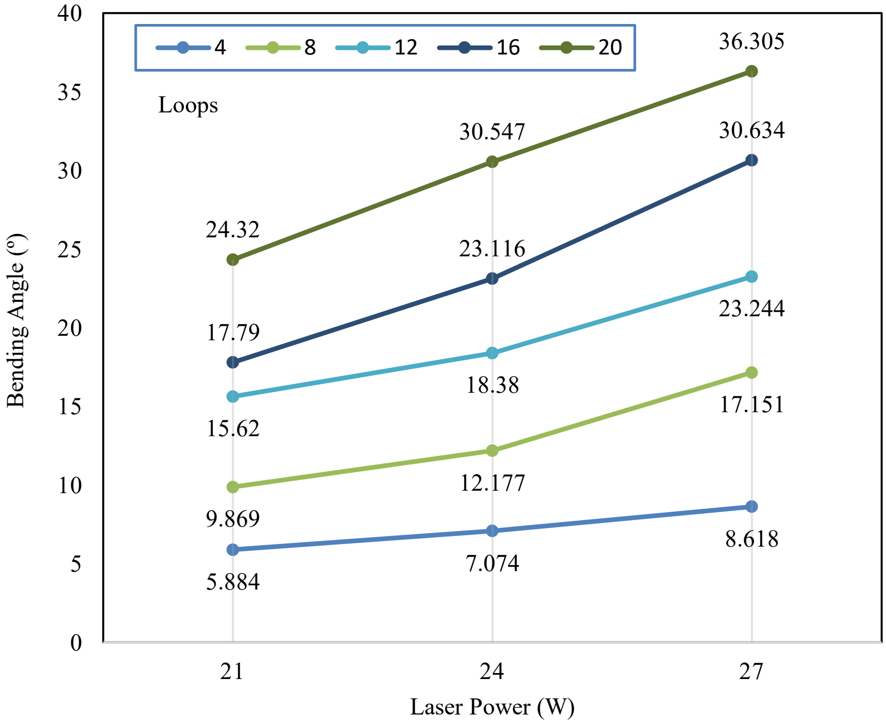


Fig. 2. Effect of laser power on bending angle formed.

All the final bending angle reading were converted into the graph in Fig. 2 and Fig. 3. Fig. 2 above shows the direct relationship between the laser power and bending angles. On the 4^{th} loop, the graph line pattern is linearly increase from lowest to highest laser power. On the 8^{th} loop, there is quite significant increase (40.85%) of the graph line pattern from 24 W to 27 W, as compared to the line from 21 W to 24 W (18.95%). There is also a significant increase for graph line on 16^{th} (72.2%) and 20^{th} (49.28%) loops, from the lowest to the highest laser power. Hence based on the graph in Fig. 2, we can observe that increasing in laser power does leads to higher bending angle. Then Fig. 3 below shows the direct relationship between laser scan passes (loops) and bending angle. For the constant laser power of 21 W, the graph line is increase significantly but not linearly from 8^{th} to 16^{th} loops with the percentage of 80.26%. For constant laser power of 24 W and 27 W, the graph pattern is increasing in quite linear and smooth pattern.

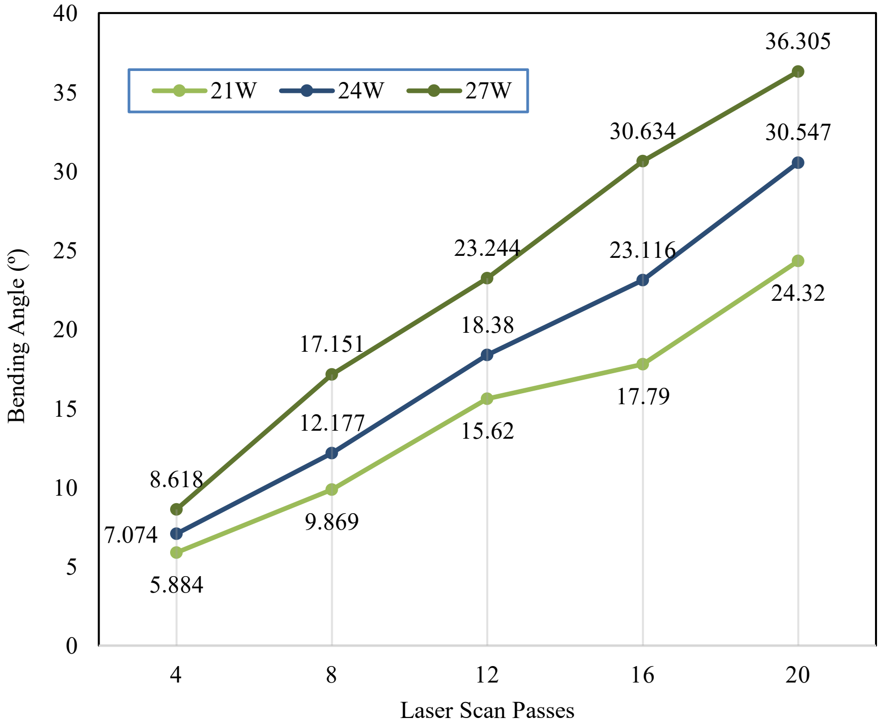


Fig. 3. The effect of laser scan passes on bending angle formed.

Table 4 below presents the average bending angle for every parametric combination. The average bending angle was obtained by using the formula in Eq. 1 below,

$$Average\ bending\ angle = \frac{(a_n)}{n} \qquad \text{Eq. 1,}$$

where a is the total bending angle after n number of passes of laser scanning. The average bending angle is the central value of angle obtained based on the number of loops performed. For example, for 16th number of loops, the bending angle for one loop using the laser power of 21 W, 24 W and 27 W is 1.112º, 1.382º and 1.915º, respectively. See Fig. 4 below which presents the average bending angle in plotted graph. For laser power of 21 W, there is a decrease in graph line from 4th loops to 8th loops and 12th loops to 16th loops. However, there are also an increase in graph line for 8th loops to 12th loops and 16th loops to 20th loops. The same pattern also occurred for 24 W laser power tested for all number of loops. As for 27 W, the graph line is in decrease pattern from the lowest to the highest number of loops. Most average bending angle were decreased as the number of loops increased.

Table 4. Average bending angle for each parametric combination.

Average Bending Angle (°)		Laser Scan Passes				
		4	8	12	16	20
Laser Power (W)	21	1.471	1.234	1.302	1.112	1.216
	24	1.769	1.522	1.532	1.382	1.527
	27	2.155	2.144	1.937	1.915	1.815

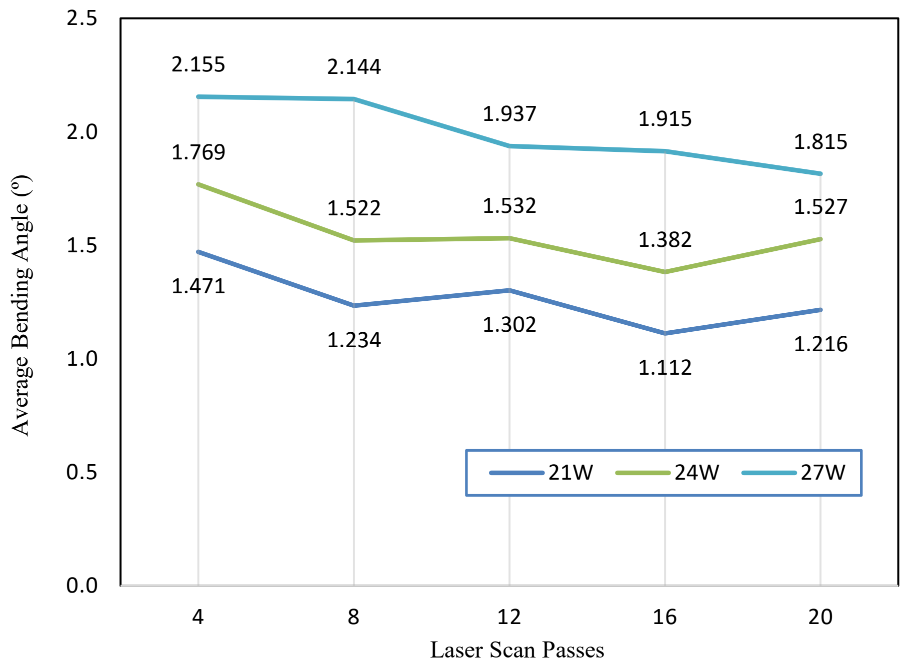


Fig. 4. The effect of laser scan passes on average bending angle.

Increasing in bending angle with increasing in laser power explains that the laser power variations decide the heat input during the laser bending process. Increasing the laser power means increasing the heat input which leads to increasing the thermal gradient in the direction of the sheet. Thus, the more plastic strain occurring which leads to larger bending angle of the sample workpiece. The effect of laser power on the bending angle can be clearly seen in Table 2. Other than laser power, it can also be seen in Table 2 that the laser scan passes also affected the changes of the bending angle. As the number of laser scan passes on the sample workpiece increased, the bending angle is also getting increased (see Fig. 3), but the average bending angle became decreased in certain locations (see Fig. 4).

There are numbers of reason that could affect the reduction in average bending angle such as, strain hardening, thermal and geometric effects due to multiple laser scan irradiations [8]. During the laser bending process, the material of the sample workpiece gets plastically deformed due to the thermal stress induced by the laser beam. With each laser scan passes to the surface of the workpiece, the bending becomes larger and the average bending angle becomes smaller, and while it produces some bending, it also leads to the increase of the density dislocation and also reduce the density energy. As the results, the sample workpiece gets strain hardened, which increases the hardness of the laser bended area, the bending per scan would reduce with an increase number of scans, resulting in the decrease of the average bending angle.

4. Conclusion

In this paper, the effect of parametric combination of laser power and laser scan passes on stainless steel AISI 304 thin sheet metal laser bending was studied. Based on the results presented, it can be concluded that;

1. Increase in laser power significantly promotes larger bending angle.
2. Increase in laser scan passes significantly promotes larger bending angle.
3. Increase in parametric combination of laser power and laser scan passes significantly increase the bending angle.
4. Increase in laser scan passes mostly promotes smaller average bending angle.

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