Iranian Journal of Materials Forming 13 (4) (2026) 48-59

IJMF

Online ISSN: 2383-0042

Iranian Journal of Materials Forming

Journal Homepage: http://ijmf.shirazu.ac.ir

Research Article

Experimental Investigation of the Effect of Scan Pattern in Three-Dimensional Laser Forming Process

Seyed Jalal Hashemi[1*], Farzad Rahmani[2], Sadegh Mirzamohammadi[1] and Mohammad Reza Ebrahimian[2]

[1] Department of Mechanical Engineering, Technical and Vocational University (TVU), Tehran, Iran
[2] Department of Mechanical Engineering, Kar Higher Education Institute, Qazvin, Iran

ARTICLE INFO

Article history:

Received: 19 May 2026
Reviewed: 6 June 2026
Revised: 15 June 2026
Accepted: 1 July 2026

Keywords:

Laser forming
Edge symmetry
Scan pattern
Bending height
Auxiliary hydraulic loading

Please cite this article as:

Hashemi, S. J., Rahmani, F., Mirzamohammadi, S., & Ebrahimian, M. R. (2026). Experimental investigation of the effect of scan pattern in three-dimensional laser forming process. *Iranian Journal of Materials Forming*, *13*(4), 48-59. https://doi.org/10.22099/IJMF.2026.56191.1384

ABSTRACT

One of the common methods in metal forming is the laser forming process. In this process, a laser beam heats the surface of the sheet, inducing thermal stresses that lead to plastic deformation of the material. Three-dimensional laser forming is a flexible manufacturing process capable of producing complex geometries without mechanical contact. In this study, the combined effects of laser scanning pattern and auxiliary hydraulic loading on the deformation behavior of circular AA1050 aluminum sheets were experimentally investigated. Four different scan patterns together with two auxiliary-loading conditions were evaluated using a full factorial design of experiments. The influences of scan pattern, beam diameter, and auxiliary hydraulic loading on bending height and edge asymmetry were statistically analyzed. A hydraulic loading system was employed to apply auxiliary loading simultaneously with laser irradiation in order to assist the forming process. The results indicate that the application of auxiliary hydraulic loading generally increased the bending deformation; however, its influence on asymmetry was less pronounced than that of the scan pattern and beam diameter. The maximum bending height of approximately 0.85 mm was achieved using the converging radial scan pattern with a beam diameter of 1.5 mm under auxiliary hydraulic loading. The minimum edge asymmetry of 0.02 mm was obtained using the circular scan pattern with 90° phase-shifted starting points, a beam diameter of 2 mm, and auxiliary hydraulic loading.

1. Introduction

The term laser stands for light amplification by stimulated emission of radiation. The theoretical foundations of lasers were first proposed by Albert Einstein in 1916; however, it took many years for industry to make the construction of the first laser possible [1]. With the introduction of a moving heat source as a forming tool, a significant transformation occurred in the field of sheet metal forming. Laser forming is one of the thermal forming processes in which a laser beam is used as the forming agent [1]. This process, which utilizes a moving heat source, has proven

* Corresponding author
E-mail address: j_hashemi@tvu.ac.ir (S. J. Hashemi)
https://doi.org/10.22099/IJMF.2026.56191.1384

especially valuable in rapid prototyping and in industries that previously required expensive molds and presses to manufacture and evaluate their products. In this method, no mechanical contact is required for forming, offering several advantages such as flexibility, ease of automation, and compatibility with other manufacturing processes. Compared to other methods, it is also more efficient in terms of raw material utilization, reducing waste. Due to the precise controllability of the laser beam position, complex and accurate shapes can be produced. Tool wear is minimal since there is essentially no contact between the tool and the workpiece, which is one of the main causes of tool failure. Tensile tests have shown that laser-formed parts exhibit better mechanical properties than conventionally formed parts [2]. The temperature gradient mechanism is the most common mechanism in laser bending processes.

The temperature gradient mechanism (TGM) is the dominant deformation mechanism in laser forming of relatively thick sheets. Rapid heating of the irradiated surface produces a temperature gradient through the sheet thickness, resulting in non-uniform thermal expansion and compressive plastic strain near the heated surface. During cooling, localized shortening of the heated layer causes permanent bending deformation. A schematic representation of the mechanism is shown in Fig. 1.

The final bending angle depends on the selected process parameters. Fauzi et al. (2019) [3] investigated the effect of laser beam profiles on edge effects and showed that a triangular profile produces the highest bending angle with minimal edge effects.

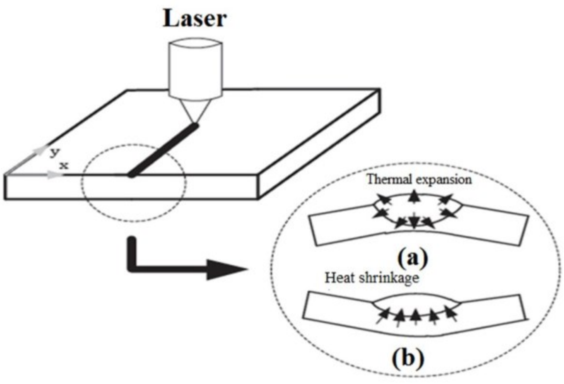

Fig. 1. Schematic of the thermal bending mechanism: (a) negative bending, (b) permanent bending of the sheet.

Tavakoli et al. [4], using numerical simulation in Abaqus, studied the effect of different scanning patterns and laser power on the bending height for producing bowl-shaped aluminum parts. They showed that a hexagonal scanning pattern results in greater bending than a circular pattern. Safari and Farzin [5], by proposing and experimentally investigating a spiral scanning pattern for laser forming of saddle-shaped geometries, made an important contribution to advancing 3D applications in laser forming. They demonstrated that modifying the irradiation path parameters provides better control over the resulting geometry. Their results showed that reducing the spiral pitch significantly increases deformation due to higher induced heat flux. Shi et al. [6] proposed methods based on applying unequal concentrated auxiliary forces alongside laser irradiation. Their results showed that by properly selecting these forces and process parameters, forming accuracy can be significantly improved. Experimental results indicated reduced bending angle deviation and improved final accuracy compared to conventional laser forming.

In the study by Gisario et al. [7], laser bending combined with external force was used to form stainless steel cubes. Parameters such as laser power, number of passes, and external force were varied to evaluate their effects on the bending angle. The results showed that increasing the number of passes and external force brought the bending angle closer to the target value of 90 °, while excessive laser power caused overheating and undesirable thermal effects. Chakraborty et al. [8] introduced a new method to improve edge symmetry in laser-formed bowl-shaped parts. In this method, high-power laser beams were applied only to the central region of a circular sheet. The bending was found to increase with irradiation time and the diameter of the central scan spot. Tavakoli et al. [9], in another study, investigated radial laser beam scanning paths for producing stainless steel bowl-shaped parts. The results indicated that converging radial paths and converging radial paths with a 30 °angular step yield the best outcomes. In the work of Wang et al. [10], a method for creating doubly curved 3D structures from flat sheets in laser forming was studied, focusing on determining optimal heating paths and laser parameters using finite element simulation. The authors first transformed target surfaces into flat sheets to determine in-plane and bending strains, and then used the obtained data to build a database of process parameters and heating paths. Khandai and Gopinath [11] investigated deformation scaling in laser forming. They experimentally and numerically studied bending behavior in multi-pass laser forming for samples with different widths, analyzing the role of multi-pass parameters on stress distribution and bending angle. Wang et al. [12] used machine learning techniques to predict bending angles and angular distortions in laser sheet forming. Based on the previous studies, no study has simultaneously investigated the effects of scanning patterns and the use of auxiliary hydraulic force to increase the bending angle and reduce edge asymmetry in laser bending.

Although external-force-assisted laser forming has been reported previously [6, 7], the loading strategies were primarily based on concentrated or localized force application. In contrast, the present study employs a hydraulic loading system combined with a circumferential steel tube to distribute the auxiliary force uniformly around the circular sheet. This configuration was specifically designed for bowl-shaped deformation of circular aluminum sheets and aims to simultaneously enhance bending deformation and improve edge symmetry. Therefore, the contribution of the present work is not merely the replacement of equipment but the introduction of a different force-transmission strategy tailored to axisymmetric laser forming applications.

Therefore, in this study, a simple hydraulic mechanism was designed to apply an auxiliary force during laser forming. Circular AA1050 aluminum sheets were subjected to single-pass laser scanning using four different scan patterns, and a full factorial design of experiments was employed to investigate the effects of scan pattern, laser beam diameter, and auxiliary-force condition on bending height and edge asymmetry. Although previous studies have investigated scan-path design, edge effects, and external-force-assisted laser forming separately, limited attention has been paid to the combined influence of scan pattern and hydraulic auxiliary force on the deformation behavior and edge symmetry of circular aluminum sheets. Furthermore, the interaction between these parameters has not been systematically evaluated using a factorial experimental design. Accordingly, the present study aims to experimentally investigate the simultaneous effects of scan pattern, laser beam diameter, and hydraulic auxiliary force on bending height and edge asymmetry in three-dimensional (3D) laser forming.

2. Experimental Equipment for Laser Forming

The sheet used in this study was made of AA1050 aluminum alloy and was cut into circular specimens with a diameter of 70 mm. The initial thickness of the aluminum sheet was 3 mm. To fix the sheet during laser scanning, a hole with a diameter of 8.5 mm was created at its center. The method of clamping the sheet using a bolt placed in the central hole is shown in Fig. 2. Due to its shiny surface, aluminum has a lower absorption coefficient for laser beams compared to steel. To improve laser absorption, the surface of the aluminum sheet was coated with graphite using a water-based graphite spray.

To improve edge symmetry and increase the bending angle in the experiments, an auxiliary-force-assisted loading condition was applied using a hydraulic mechanism. Considering the circular geometry of the sheet and the target shape, a steel tube was used to apply the auxiliary force so that the applied pressure was uniformly distributed along the circumferential direction of the sheet. The mechanism used to apply the auxiliary force is shown in Fig. 3(a). The outer diameter of the tube used in this mechanism was 50 mm, and its thickness was 3 mm.

Fig. 2. The location of the workpiece clamp on the fixture.

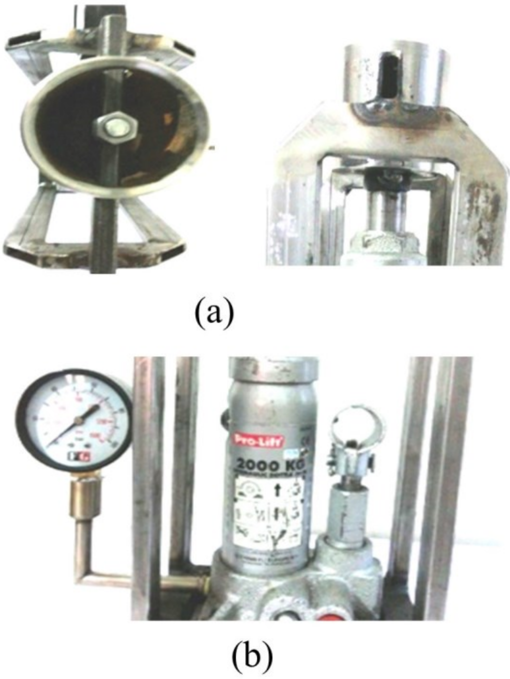

Fig. 3. (a) Steel tube used for auxiliary-force application, (b) hydraulic jack used to generate the auxiliary force.

The required force was generated using a 2-ton hydraulic jack, and its magnitude was controlled by the oil pressure inside the jack using a pressure gauge installed on it (Fig. 3(b)). The auxiliary loading condition was controlled by regulating the hydraulic pressure of the jack. Direct measurement of the contact force was not performed; however, a consistent loading condition was maintained throughout the experimental runs by keeping the auxiliary force condition setting constant for each test condition. A fiber laser system with nitrogen as a shielding gas was used for the forming process. The laser power was 1000 W, frequency 2000 Hz, scanning speed 100 mm/min, and shielding gas pressure 1 bar. Fig. 4 shows the positioning of the auxiliary force mechanism and the initial sheet on the laser machine table. A coordinate measuring machine (CMM) was used to measure the edge symmetry of the formed parts. Prior to measuring the formed specimens, the initial flat sheet was used as the reference datum for evaluating out-of-plane deformation. All measurements were performed using the same fixture and coordinate system to minimize positioning variability. The CMM was selected because its measurement accuracy was significantly smaller than the magnitude of the observed deformation responses. Consequently, the measured differences in bending height and asymmetry were considered detectable within the capability of the measurement system. In this method, the probe of the CMM was moved along the edge of the formed sheet, and the coordinates of all points were recorded. Four different scanning patterns were used to induce bending in the circular aluminum sheet, as schematically illustrated in Fig. 5.

Fig. 6 schematically illustrates the experimental setup and the forming procedure. The circular AA1050 aluminum sheet was fixed at its center using a bolt-and-nut assembly through a pre-drilled central hole.

Fig. 4. Placing the auxiliary force mechanism and blank on the laser machine.

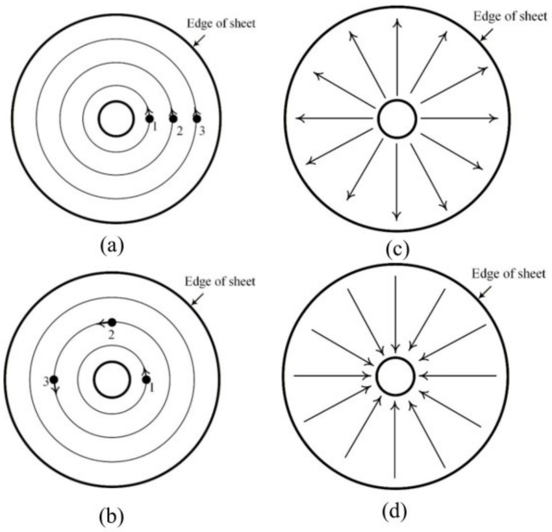

Fig. 5. Laser scanning patterns: (a) circular with the same starting point, (b) circular with starting points separated by 90°, (c) divergent radial, and (d) convergent radial.

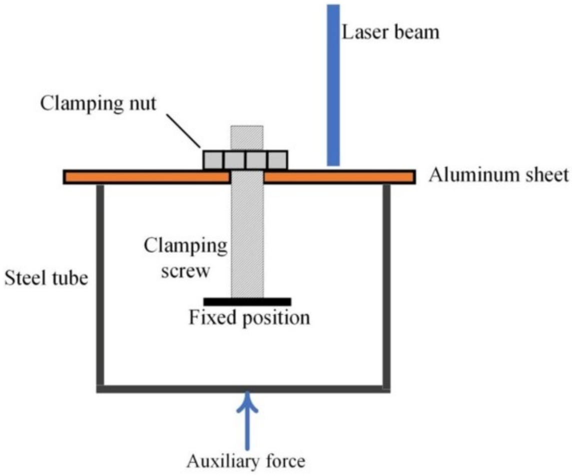

Fig. 6. Schematic illustration of the experimental setup and the hydraulic force-assisted laser forming process.

During the experiments, the laser beam was irradiated from the upper surface of the sheet following the selected scan patterns, resulting in upward bending deformation while the sheet center remained constrained. To enhance the upward deformation, an auxiliary loading system was employed. As shown in the schematic, a steel tube was positioned beneath the sheet edge and applied an upward supporting force simultaneously with laser irradiation. The upward force was generated by a hydraulic jack and transmitted through the steel tube to the sheet. This arrangement was designed to assist the laser-forming process by promoting upward edge movement and increasing the resulting bending deformation.

As shown in Fig. 6, the steel tube was positioned beneath the peripheral region of the circular sheet and remained in contact with the sheet edge during laser irradiation. The tube provided circumferential support and transmitted the auxiliary force generated by the hydraulic jack.

3. Experimental Design

The experiments were conducted to investigate the effects of the main process parameters on the characteristics of laser-based 3D forming using a full factorial design implemented in Minitab. In this approach, all possible combinations of parameter levels are considered to accurately evaluate both the individual and interaction effects of the parameters on the process responses. In this study, three main influencing parameters were examined: laser scanning pattern, presence or absence of auxiliary loading, and laser beam diameter. The scanning pattern was defined at four levels: circular with identical starting point, circular with 90 °phase shift, diverging radial, and converging radial. The auxiliary loading parameter was considered at two levels (“with auxiliary loading and without auxiliary loading), and the laser beam diameter was set at two levels: 1.5 mm and 2 mm.

Using Minitab, a full factorial design with four levels for the scanning pattern, two levels for auxiliary loading, and two levels for laser beam diameter was developed and implemented. The objective of this experimental design was to simultaneously evaluate the effects of process parameters on the desired responses and to determine the optimal conditions for laser-based 3D forming.

4. Results and Discussion

4.1. Experimental design results

The data obtained from 16 experimental runs based on the full factorial design are presented in Table 2. To reduce systematic errors, prevent unintended bias, and increase the accuracy and reliability of the results, the order of experiments was completely randomized. Randomization helps minimize the influence of uncontrolled nuisance factors, ensuring that the observed variations in responses are mainly due to the investigated input parameters.

Table 1. Parameters used in experimental tests of the 3D laser forming process

Factors	Level 1	Level 2	Level 3	Level 4
Scan pattern	Circular starting at the same time (a)	Circular 90 degrees apart (b)	Radial diverging (c)	Radial converging (d)
Auxiliary force condition	With auxiliary force condition (wp)	Without auxiliary force condition (np)		
Laser beam diameter	1.5	2		

Table 2. Experimental results

No.	Scan pattern	Presence of auxiliary force condition	Laser beam diameter	**Height**	**Asymmetry**
1	c	w p	2	0.65	0.028
2	a	n p	2	0.65	0.023
3	d	w p	2	0.76	0.03
4	a	w p	2	0.31	0.021
5	b	w p	2	0.71	0.02
6	d	w p	1.5	0.85	0.033
7	c	n p	1.5	0.58	0.035
8	b	n p	2	0.29	0.023
9	a	w p	1.5	0.35	0.025
10	b	w p	1.5	0.8	0.023
11	b	n p	1.5	0.71	0.025
12	d	n p	1.5	0.72	0.037
13	c	w p	1.5	0.7	0.031
14	a	n p	1.5	0.31	0.024
15	c	n p	2	0.63	0.022
16	d	n p	2	0.68	0.028

Four laser-bent samples are shown in Fig. 7. To better visualize the amount of bending, an unformed (raw) sheet was placed next to each sample for comparison. It is worth noting that in all experiments, the laser beam scanned the predefined paths only once. As mentioned earlier, a coordinate measuring machine (CMM) was used to measure edge asymmetry. After determining the coordinates of all points along the edge, a two-dimensional curve was plotted to evaluate the variation around the circumference of the formed sheet. The profile corresponding to Experiment No. 1 (Table 2) is shown in Fig. 8. The difference between the highest and lowest points of the plotted curve was considered as the measure of edge asymmetry.

Table 2, in addition to presenting the measured response values, shows the combinations of process parameters for each experiment, including the laser scanning pattern, auxiliary loading, and laser beam diameter. These data formed the basis for subsequent statistical analyses, including evaluation of main effects, interaction effects, and analysis of variance (ANOVA), to assess the influence of each factor on the characteristics of laser-based 3D forming.

4.2. Statistical analysis of asymmetry

To verify the assumptions of the analysis of variance(ANOVA), the normality of the model residuals was evaluated, and the results indicated a good agreement with the normal distribution. The ANOVA results (Table 3) show that the proposed model explains 90.9% of the variation in asymmetry. The linear effects of the parameters were statistically significant (P = 0.038),

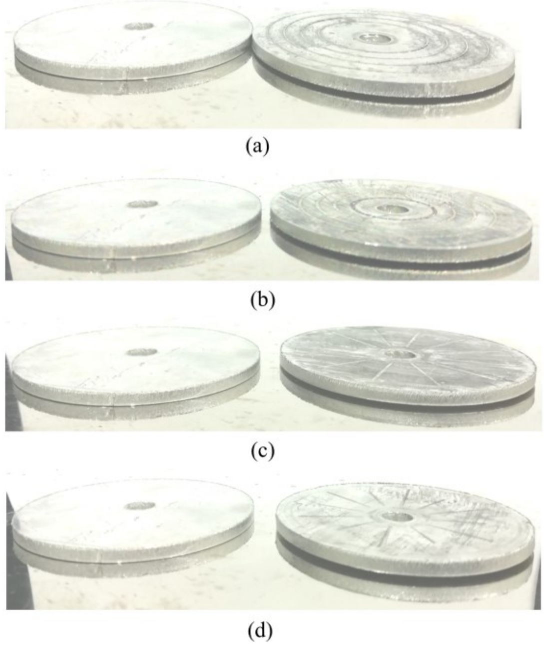

Fig. 7. (a) Circular with the same starting point (Experiment No. 1), (b) circular with starting points separated by 90° (Experiment No. 2), (c) divergent radial scan pattern (Experiment No. 3), and (d) convergent radial (Experiment No. 4).

while the two-factor interaction effects did not have a significant influence on the response. Among the main factors, the laser scanning pattern, with the highest contribution (60.72%, P = 0.030), was identified as the most influential factor affecting asymmetry. This was followed by the laser beam diameter, which showed a significant effect with a contribution of 22.51% (P = 0.035). The auxiliary loading did not have a statistically significant effect on asymmetry. Although the high R^2 value indicates a good fit of the model, the reduction in adjusted and predicted R^2 suggest reduced predictive capability outside the experimental design space. Overall, the results indicate that controlling the scanning pattern and laser beam diameter plays a key role in reducing asymmetry in laser-based 3D forming. Fig. 9 shows the normal probability plot of the residuals, indicating that the data points mostly lie along the reference line with no significant deviation or outliers. This confirms the approximate normality of residuals and the suitability of the statistical model for analyzing the results.

The beneficial effect of increasing the beam diameter can be attributed to the heat flux over a larger surface area, which promotes a more uniform temperature field and consequently a more homogeneous plastic deformation. Overall, the main effects plot confirms that the laser scanning pattern is the most influential parameter on asymmetry, and its proper selection, along with beam diameter control, plays a key role in improving the quality of laser-based 3D forming.

The dominant influence of the laser scan pattern on asymmetry can be attributed to differences in thermal energy distribution across the sheet surface. Circular scan paths provide a more uniform circumferential heat input, resulting in homogeneous thermal expansion and reduced edge deviation. In contrast, radial scan paths concentrate thermal energy along discrete trajectories, generating localized thermal gradients and uneven plastic strain accumulation. The statistically insignificant interaction effects indicate that the influence of scan pattern remains dominant across different beam diameters and auxiliary loading conditions. Therefore, the investigated factors primarily affect asymmetry through independent mechanisms rather than through strong coupled interactions.

4.3. Statistical analysis of bending height

The results of the analysis of variance (ANOVA) for the height response are presented in Table 4. According to these results, the overall model explains approximately 87.11% of the variation in the response, indicating a relatively good explanatory capability. However, the model P-value is 0.200, suggesting that the overall model is not statistically significant at the 95% confidence level. Examination of the linear effects shows that although they account for a considerable

Table 3. The results of the electromagnetic stress relief operation

Source	DF	Seq SS	Contribution (%)	Adj SS	Adj MS	F-Value	P-Value
Model	11	0.000364	90.90	0.000364	0.000033	3.63	0.112
Linear	5	0.000336	83.79	0.000336	0.000067	7.36	0.038
A	3	0.000243	60.72	0.000244	0.000081	8.89	0.030
B	1	0.000002	0.56	0.000002	0.000002	0.25	0.646
C	1	0.000090	22.51	0.000090	0.000090	9.89	0.035
2-Way Interactions	6	0.000029	7.11	0.000029	0.000005	0.52	0.774
A × B	3	0.000006	1.56	0.000006	0.000002	0.23	0.873
A × C	3	0.000022	5.55	0.000022	0.000007	0.81	0.550
Error	4	0.000037	9.10	0.000037	0.000009	—	—
Total	15	0.000401	100.00	—	—	—	—

S	R^2 (%)	R^2(adj) (%)	R^2(pred) (%)	PRESS
0.00	0.000584	65.87	90.90	0.00302

Table 4. Analysis of variance for height

Source	DF	Seq SS	Contribution (%)	Adj SS	Adj MS	F-Value	P-Value
Model	11	0.449125	87.11	0.449125	0.040830	2.46	0.200
Linear	5	0.280750	54.45	0.280750	0.056150	3.38	0.131
A	3	0.253925	49.25	0.253925	0.084642	5.10	0.075
B	1	0.019600	3.80	0.019600	0.019600	1.18	0.338
C	1	0.007225	1.40	0.007225	0.007225	0.43	0.546
2-Way interactions	6	0.168375	32.66	0.168375	0.028063	1.69	0.318
A × B	3	0.083850	16.26	0.083850	0.027950	1.68	0.307
A × C	3	0.084525	16.39	0.084525	0.028175	1.70	0.305
Error	4	0.066450	12.89	0.066450	0.016613	—	—
Total	15	0.515575	100.00	—	—	—	—

S	R^2 (%)	R^2(adj) (%)	R^2(pred) (%)	PRESS
0.00	1.0632	51.67	87.11	0.128889

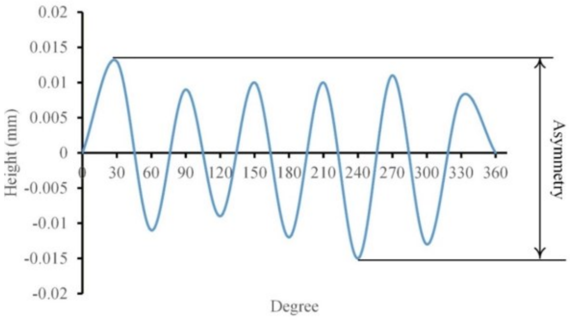

Fig. 8. Determination of asymmetry for Experiment No. 1.

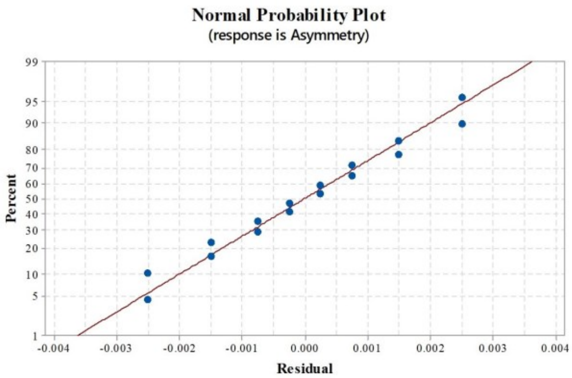

Fig. 9. Normal probability plot of the residuals for the asymmetry model.

portion of the response variation (54.45%), they are not statistically significant at the desired confidence level (P = 0.131). Among the main parameters, the laser scanning pattern (A) has the highest contribution (49.25%) with a P= 0.075, indicating a relatively strong influence on bending height, although this effect does not reach statistical significance at the 95% confidence level. In contrast, auxiliary loading (B) and laser beam diameter (C) do not show statistically significant effects on the height response. The two-factor interaction effects collectively account for 32.66% of the response variation; however, none of these interactions are statistically significant. The statistical indicators of the model show that the R^2 value is 87.11%, confirming a good fit to the experimental data. Nevertheless, the reduction in adjusted and predicted R^2 values indicates reduced predictive capability outside the experimental design space. Overall, the statistical analysis indicates that the laser scanning pattern exhibited the strongest observed influence on bending height; However, this effect did not reach statistical significance at the 95% confidence level (P = 0.075).

The normal probability plot for height values is shown in Fig. 10. The data points lie close to the reference line, indicating better predictive accuracy of the model.

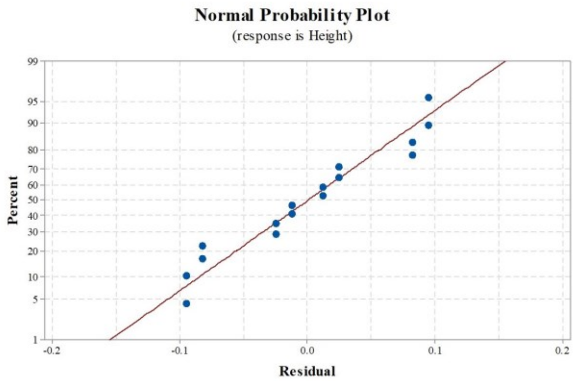

Fig. 10. Normal probability plot of the residuals for the bending-height model.

The observed effect of scan pattern on bending height is mainly associated with the spatial distribution of thermal stresses. Converging radial paths concentrate thermal energy toward the central region of the sheet, promoting greater thermal softening and localized plastic deformation, which increases the bending height. The absence of statistically significant interaction effects suggests that variations in beam diameter and auxiliary loading do not fundamentally alter the thermal deformation mechanism within the investigated range. Consequently, the overall deformation behavior is primarily governed by the temperature distribution imposed by the selected scan pattern.

4.4. Main effects of parameters on asymmetry

Fig. 11 presents the main effects plot, showing the mean asymmetry response at different levels of process parameters. As observed, the laser scanning pattern (A) has the most significant effect on asymmetry, with noticeable changes in mean values across different patterns. The lowest asymmetry corresponds to the circular scanning pattern with a 90°phase shift (b), while the highest asymmetry is observed in the converging radial pattern (d). This trend highlights the critical role of laser energy distribution in achieving uniform deformation in the 3D laser forming process. In circular scanning patterns, the more uniform distribution of laser energy over the sheet surface, higher symmetry can be expected. However, in the circular pattern with the same starting point, the heat distribution is less uniform, leading to increased asymmetry. In radial patterns, the continuity of laser motion along the circumferential path is disrupted. As a result, the heat flux is highly concentrated along radial paths, while the regions between these paths experience lower temperatures, leading to greater edge symmetry. In the converging radial pattern, because the heat flux originates near the sheet edge, the temperature distribution becomes non-uniform, increasing asymmetry. The auxiliary loading parameter (B) shows a relatively limited effect on asymmetry. The small difference between the mean values obtained with and without auxiliary loading indicates that this parameter plays a secondary role in controlling asymmetry, which is consistent with the ANOVA results. The application of auxiliary-loading showed a tendency to increase the bending magnitude. However, based on the ANOVA results, its effect on asymmetry was not statistically significant. Therefore, the influence of auxiliary loading on symmetry should be considered limited compared with the dominant effect of scan pattern. It should be emphasized that the auxiliary force condition system was intended to assist the laser-forming process rather than act as an independent forming mechanism. The steel tube primarily serves as a support and force-transmission element, while deformation is generated through the combined action of laser-induced thermal stresses and auxiliary force condition. Although the present study did not include a dedicated decoupling analysis to quantify the individual contributions of thermal and mechanical effects, the relatively small contribution of auxiliary force condition in the ANOVA results suggests that the scan-pattern-induced thermal field remains the dominant factor governing asymmetry. A detailed quantitative separation of thermal and mechanical contributions is recommended for future investigations. Regarding the laser beam diameter (C), reducing the diameter from 2 mm to 1.5 mm increases the mean asymmetry. This trend indicates that higher energy concentration and increased thermal gradients intensify deformation non-uniformity, leading to greater asymmetry.

4.5. Main effects of parameters on bending height

Fig. 12 shows the main effects of parameters on height,

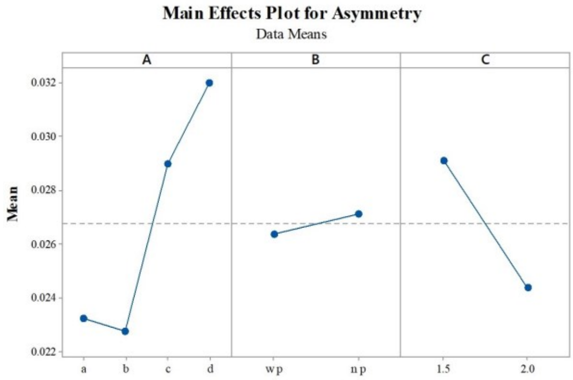

Fig. 11. Main effects plot of process parameters on asymmetry.

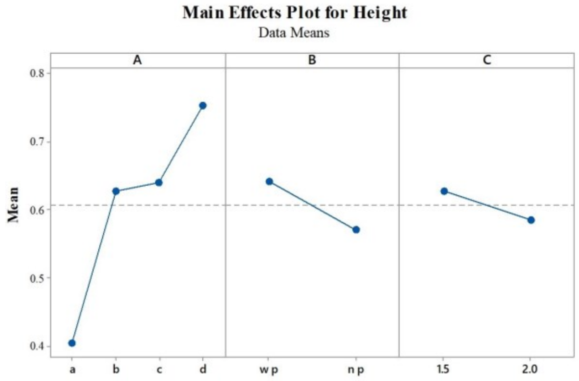

Fig. 12. Main effects plot of process parameters on bending height.

illustrating the variation of mean height across different parameter levels. As seen, the laser scanning pattern (A) has the most significant influence on height, with noticeable changes in mean values across different patterns. The lowest height corresponds to the circular scanning pattern with the same starting point (a), while the highest height is observed in the converging radial pattern (d). This trend reflects the dominant role of laser energy distribution in determining the extent of deformation. In radial scanning patterns, laser energy is concentrated along specific paths, resulting in localized plastic deformation and greater bending. However, it should be noted that increased bending height in these patterns is accompanied by increased asymmetry. The converging radial pattern produces the highest bending but also leads to maximum asymmetry. The auxiliary loading parameter (B) shows a mild increasing effect on height, as removing the auxiliary loading results in reduced mean height. The application of auxiliary loading resulted in a higher average bending height compared with the no-force condition. However, according to the ANOVA results, this observed difference was not statistically significant within the investigated range. Applying pressure simultaneously with laser irradiation, especially considering thermal softening of the sheet, leads to greater bending. For the laser beam diameter (C), increasing the diameter from 1.5 mm to 2 mm reduces the mean height. This behavior can be attributed to wider energy distribution and lower effective power density on the surface, resulting in reduced vertical deformation. Due to the high thermal conductivity of aluminum, especially at larger beam diameters, the heat flux cannot locally raise the temperature sufficiently, leading to reduced plastic deformation caused by thermal gradients. Overall, the results indicate that the laser scanning pattern is the most influential factor on height, and its proper control, along with beam diameter and auxiliary force condition, plays an important role in achieving the desired height in laser-based 3D forming.

A trade-off exists between maximizing bending height and minimizing edge asymmetry. The convergent radial pattern generated the highest deformation, whereas the circular pattern with 90° phase-shifted starting points provided the best symmetry. Therefore, the preferred scan pattern depends on the intended application. For applications requiring dimensional accuracy and geometric uniformity, the circular 90° phase-shifted pattern is recommended. Conversely, when maximum deformation is the primary objective, the convergent radial pattern is more suitable.

The selected laser processing parameters were chosen based on conditions reported in previous laser-forming studies operating within the temperature-gradient mechanism (TGM) regime. During visual inspection of the processed specimens, no obvious signs of excessive surface damage, material ejection, or collapse were observed. However, since metallographic characterization was not conducted in the present study, the occurrence of localized melting cannot be completely ruled out. Therefore, detailed microstructural examination of the laser-affected zone is recommended in future work to verify the deformation mechanism under the investigated processing conditions.

5. Conclusion

The main findings of this study can be summarized as follows:

1. Among the investigated parameters, the laser scanning pattern exhibited the strongest observed influence on both bending height and edge asymmetry.

2. The convergent radial scan pattern generated the highest bending height, reaching approximately 0.85 mm under the investigated processing conditions.
3. The circular scan pattern with 90° phase-shifted starting points produced the lowest edge asymmetry, demonstrating superior geometric uniformity.
4. The application of auxiliary-loading showed a tendency to increase bending deformation, while its influence on edge asymmetry was less pronounced compared to the scan pattern effect.
5. Increasing the laser beam diameter reduced bending height while improving edge symmetry due to the more uniform distribution of thermal energy.

The present study has several limitations. First, experimental replication was not performed; therefore, the ANOVA results should be interpreted primarily as indicators of relative factor influence and observed trends rather than definitive statistical confirmation of all effects. Second, metallographic characterization of the laser-affected zone was not conducted, preventing direct verification of the absence of localized melting. Future work should address these limitations through replicated experiments, uncertainty analysis, and detailed microstructural investigations. In addition, the applied auxiliary loading was not directly measured, and a detailed uncertainty analysis of the small deformation responses was not performed. These aspects should be considered in future studies to improve the quantitative reliability of the results.

Future work should focus on multi-pass laser forming, detailed thermal-mechanical modeling, uncertainty quantification, and the investigation of the individual contributions of thermal and mechanical loading mechanisms.

Author's contributions

S. J. Hashemi: Conceptualization, Validation, Formal analysis, Writing-original draft, Supervision

F. Rahmani: Methodology, Investigation, Data curation

S. Mirzamohammadi: Conceptualization, Material preparation, Data collection, Data analysis, Design

M. R. Ebrahemian: Conceptualization, Material preparation, Data collection, Data analysis

Competing interests

The authors declare no conflict of interest.

Funding

The authors hereby announce that no part of this study was funded by any institutions and/or organizations.

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