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Experimental Evaluation, Modeling and Statistical Analysis of Laser Forming Process of Curved Tubes

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ABSTRACT

The laser forming process aimed at fabricating curved tubes from initially straight tubes using an irradiation scheme with parallel straight lines is experimentally studied. The effects of laser parameters—laser output power, laser scanning speed, laser beam diameter and number of irradiating lines—on the radius of curvature (RC) of laser formed tubes are investigated. The design of experiment (DOE) method based on response surface methodology (RSM) is employed to accurately and comprehensively analyze the effects of each input parameter and their interactions on the RC. The results demonstrate that the proposed irradiation scheme successfully produces curved tubes from straight tubes. It is also concluded that increasing the laser output power and number of irradiating lines decreases the RC, while increasing in the laser scanning speed and laser beam diameter increases the RC. Optimization of the input parameters indicates that to achieve the minimum RC, the laser output power, laser scanning speed, laser beam diameter and number of irradiating lines should be set to 115 W, 2 mm/s, 1 mm and 75, respectively.

1. Introduction

Tubular specimens are widely used in many industries, such as aerospace and automotive, due to their effectiveness in shock absorption. However, forming tubular parts using mechanical tools often results in issues like wrinkling, wall thinning, ovality and thickness variations across the cross-section. The forming of tubular parts using a laser beam can considerably reduce many of these problems. Laser forming of tubular specimens leads to the fabrication of 2D and 3D tubes with minimal ellipticity, wall thinning, and thickness variations. In recent years, some research has been conducted in the field of laser tube forming, most of which has focused on the 2D laser tube forming. Some of these studies are mentioned below.

Kraus [1] and Slive et al. [2] investigated the laser tube bending process (LTBP) of square cross-section specimens through numerical simulations and

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experimental testing. Li and Yao [3] studied the effect of process parameters on the bending angle of laser bent tubes. Hsieh and Lin [4] employed a coupled thermo-mechanical model to simulate the LTBP and analyze the deformation behavior of laser bent tubes. Zhang et al. [5] explored the influence of heating patterns on the final bending angle. Guan et al. [6] used finite element simulations to examine the mechanics of deformation in LTBP. Wang et al. [7] proposed a geometric algorithm for laser forming of 2D and 3D tubular parts. Jamil et al. [8] investigated micro-scale laser bending of nickel tubes through experimental and numerical approaches. Imhan et al. [9] examined changes in material properties of the tubes irradiated by the laser beam. Safari [10] studied the effects of heating length and the number of heating passes on the resulting bending angle of laser bent tubular parts. Khandandel et al. fabricated 2D and 3D tubular parts using a novel method [11] and studied the role of forced cooling in improving the bending angle [12]. Keshtiara et al. [13] applied artificial neural networks and genetic algorithms to predict bending angles in laser bent tubes. As evident from the literature review, most investigations in the field of laser forming of metallic tubes have focused on simple bending processes. In contrast, studies dedicated to the manufacturing of curved tubes from straight ones using laser beams are relatively rare. Therefore, this research addresses the production of curved tubes from straight tubes through laser forming. In this study, an appropriate irradiation pattern, the laser forming process of curved tubes is analyzed. For this purpose, an irradiation pattern consisting of linear parallel heating lines is utilized, and the production of curved tubes is explored. Using the design of experiments (DOE) method, a comprehensive investigation has been conducted into the effects of process parameters—such as laser output power (LOP), laser scanning speed (LSS), laser beam diameter (LBD) and number of irradiating lines (NIL)—on the most important characteristic of the fabricated tubular part, namely, the radius of curvature (RC).

2. Experimental Procedure

A CO_2 laser machine with continuous wave mode and a maximum output power of 120 W was used for the experiments. The initial tube material was mild steel, with a length of 400 mm, an outer diameter of 50 mm, and a wall thickness of 2 mm. Since the primary characteristic to be measured in the laser formed tubes is the radius of curvature, a coordinate measuring machine (CMM-Easson ENC-565) was used for RC evaluating. The experimental setup for the laser tube forming process is illustrated in Fig. 1.

As mentioned earlier, to conduct a comprehensive study on the effect of input process parameters on the RC, the DOE method based on response surface methodology (RSM) is employed. Four critical process parameters—laser output power, laser scanning speed, laser beam diameter, and number of irradiating lines—are selected as input variables, while the RC of the deformed tubes is considered the output response. To determinethe appropriate range for these laser parameters, several preliminary trial-and-error tests were carried out. The selected levels for each input parameter are presented in Table 1, and the experimental design generated using the RSM method is shown in Table 2.

Fig. 1. The experimental setup of the laser tube forming process and the resulting laser formed tubes.

Table 1. Levels of input parameters used in the laser tube forming process

Input variables	Symbol	Min value	Mid value	Max value
Laser output power [W]	P	85	100	115
Laser scanning speed [mm/s]	S	2	6	10
Laser beam diameter [mm]	D	1	2	3
Number of irradiating lines	N	25	50	75

Table 2. Experimental runs based on the Box-Behnken design

Experiment number	P	S	D	N
1	100	6	2	50
2	85	6	3	50
3	85	10	2	50
4	100	6	2	50
5	115	6	2	25
6	85	6	2	75
7	100	2	2	25
8	100	6	3	75
9	100	10	2	25
10	115	6	2	75
11	100	6	3	25
12	115	6	1	50
13	100	6	1	25
14	85	2	2	50
15	100	6	1	75
16	100	10	2	75
17	100	2	3	50
18	85	6	2	25
19	115	10	2	50
20	85	6	1	50
21	100	10	1	50
22	100	6	2	50
23	115	2	2	50
24	100	10	3	50
25	115	6	3	50
26	100	2	1	50
27	100	2	2	75

3. Results and Discussion

3.1. Effect of process parameters on the radius of curvature of laser formed tubes

The RC of laser formed tubes using an irradiation scheme with parallel heating lines was measured, and the results of the analysis of variance (ANOVA) are presented in Table 3. Two points are important when analyzing the ANOVA results. First, parameters with P-values less than 0.05 are considered significant and have a notable effect on the RC of the deformed tubular parts. Second, parameters with larger F-values indicate a greater influence on the RC. In addition, as shown in Fig. 2, a Pareto diagram is plotted based of the RC analysis.

Examining the results in Table 3 reveals that all laser input parameters have a significant effect on the RC. Furthermore, based on the P-values and F-values, it is observed that the number of NIL, LSS, LOP and LBD have the greatest impact on the RC of deformed tubes, respectively.

It can be concluded from Table 3 that the squares of all the input parameters have a significant effect on the RC. Additionally, the interaction between LOP and LSS significantly influences the RC of the tubes. Based on the regression analysis results and considering the range of laser input parameters in this study, Eq. (1) has been derived to calculate the RC of tubes as a function of the input parameters.

$$\begin{aligned}\textbf{RC (mm)} &= 19.0 + 2.87\ P + 45.38\ S + 54.0\ D \\ &+ 2.667\ N - 0.01733\ P{*}P - 1.832\ S{*}S - 9.01\ D{*}D \\ &- 0.04016\ N{*}N - 0.0708\ P{*}S\end{aligned} \quad (1)$$

The coefficient of determination “R^2” is used to quantify the agreement between the model’s predicted data and the experimental results. For a theoretically perfect statistical model, R^2 equals 1. In this study, the R^2 value calculated for the RC of the deformed tubes is 0.9981. This indicates that the proposed model can accurately predict 99.81% of the experimental data, leaving only 0.19% of the total variation unexplained. The residual plots for the model used in this research are presented in Fig. 3, which demonstrate that the employed model can precisely predict the RC of tubes.

It is evident from Fig. 4 that with increasing LOP, the RC of the tube decreases. This can be explained by the

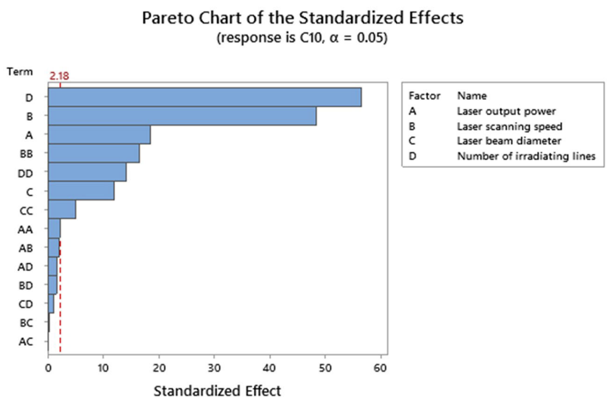

Fig. 2. Pareto diagram plotted based of the analysis of RC.

Table 3. Analysis of variance (ANOVA) results for laser formed tubes

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	14	107806	7700.4	459.08	0.000
Linear	4	100978	25244.4	1505.00	0.000
P	1	5795	5794.8	345.47	0.000
S	1	39331	39330.8	2344.79	0.000
D	1	2425	2425.4	144.59	0.000
N	1	53427	53426.7	3185.15	0.000
Square	4	6642	1660.5	98.99	0.000
P*P	1	81	81.1	4.84	0.048
S*S	1	4583	4582.5	273.20	0.000
D*D	1	433	433.2	25.83	0.000
N*N	1	3360	3360.1	200.32	0.000
2-Way interaction	6	187	31.1	1.85	0.171
P*S	1	72	72.3	4.31	0.060
P*D	1	0	0.3	0.01	0.905
P*N	1	51	51.1	3.05	0.106
S*D	1	2	2.2	0.13	0.721
S*N	1	42	42.2	2.52	0.138
D*N	1	18	18.5	1.10	0.314
Error	12	201	16.8		
Lack-of-fit	10	198	19.8	12.68	0.075
Pure error	2	3	1.6		
Total	26	108007			

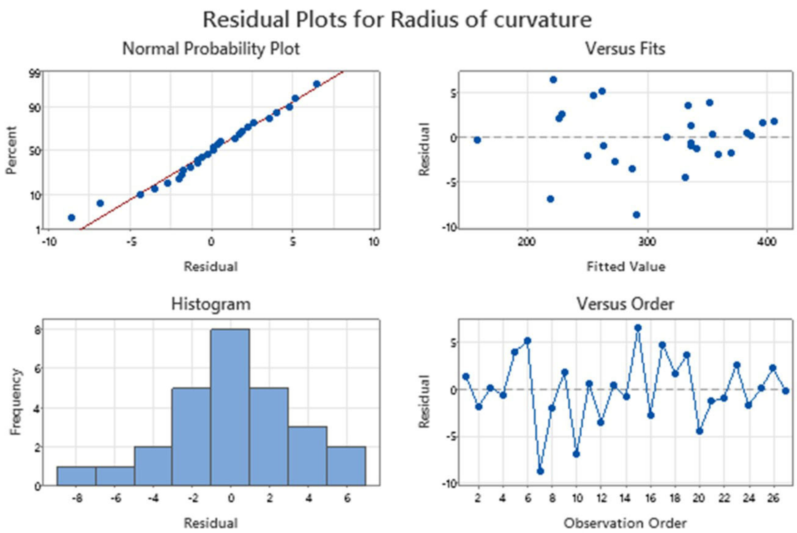

Fig. 3. Residual plots of the employed model in the laser tube forming process.

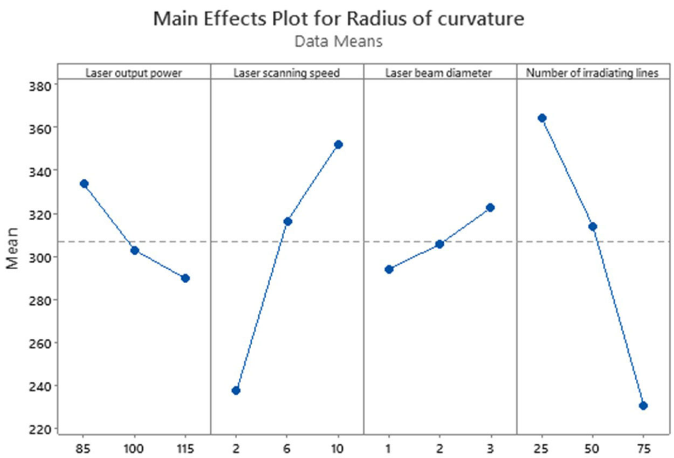

Fig. 4. The effects of input parameters on RC of deformed tubes.

fact that the amount of thermal energy irradiated into the tube increases as LOP increases. Consequently, more plastic strains are generated in the tube, leading to greater plastic deformations. Hence, the RC of the deformed tube decreases. In addition, Fig. 4 shows that the RC increases with increasing LSS. This is because, as LSS increases, the time available for thermal energy to enter the tube is reduced, in other words, less thermal energy is absorbed by tube. This reduction in heat input lowers thermal and plastic strains, resulting in less deformation and thus an increased RC. It is concluded from Fig. 4 that with an increase in LBD, the RC of the deformed tube increases. This is because, as the laser beam diameter increases, the thermal energy delivered to the tube decreases. Consequently, the thermal and plastic strains created in the irradiated areas of the tube are reduced. A reduction in the plastic deformation regions of the tube means that the overall deformation induced in the laser formed tube decreases, and as a result, the RC of the tube increases. It can be seen from Fig. 4 that increasing NIL in the parallel line irradiation pattern reduces the RC of the deformed tube. This occurs because more irradiating lines increase the total thermal energy input, which creates higher thermal and plastic strains. Therefore, as the areas with plastic deformation in the tube increase, the deformation induced in the laser formed tube also increases, resulting in a decrease in the RC of the tube. To further clarify the effects of the input parameters on the RC of the tube, the interactions between these parameters are illustrated using two-dimensional contour plots. In Fig. 5 the interactions between LOP - LSS, LOP - LBD and LOP - NIL and their effects on the RC of the laser formed tube are presented. As shown in Fig. 5, increasing the LOP while decreasing the LSS leads to a reduction in the RC of the deformed tube. Similarly, increasing the LOP in combination with decreasing the LBD results in a lower RC. In addition, a simultaneous increase in LOP and NIL also leads to a decrease in the RC.

Moreover, Fig. 6 shows the interactions between LSS - LBD and LSS - NIL and their effects on the RC of the deformed tube. It can be concluded from Fig. 6 that a decrease in both LSS and LBD leads to a reduction in the RC of tube. Additionally, a decrease in LSS combined with an increase in NIL also results in a decrease in the RC.

The interaction between LBD and NIL and their effects on the RC of deformed tube is presented in Fig. 7. It can be concluded from Fig. 7 that a decrease in LBD combined with an increase in NIL results in a reduction in the RC of the tube.

3.2. Optimal condition

The optimal values of laser parameters such as LOP, LSS, LBD and the NIL, required to minimize the RC of the laser formed tube are shown in Fig. 8. This section aims to determine the appropriate setting of each input parameter (within the ranges listed in Table 1) to achieve the lowest possible RC in the deformed tube. Based on the optimization analysis, the result was obtained as follows: By adjusting the LOP = 115 W, the LSS = 2 mm/s, the LBD = 1 mm, and the NIL = 75, the RC equal to 113 mm can be achieved.

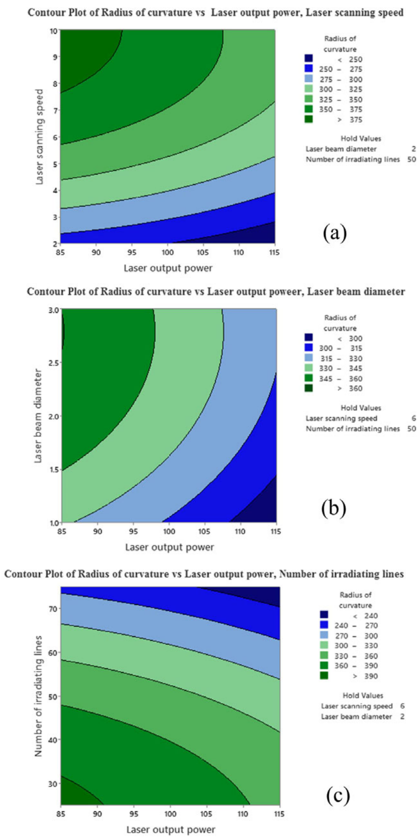

Fig. 5. Interactions between LOP and other input parameters and their effects on the RC of tube: (a) LOP - LSS, (b) LOP - LBD, and (c) LOP - NIL.

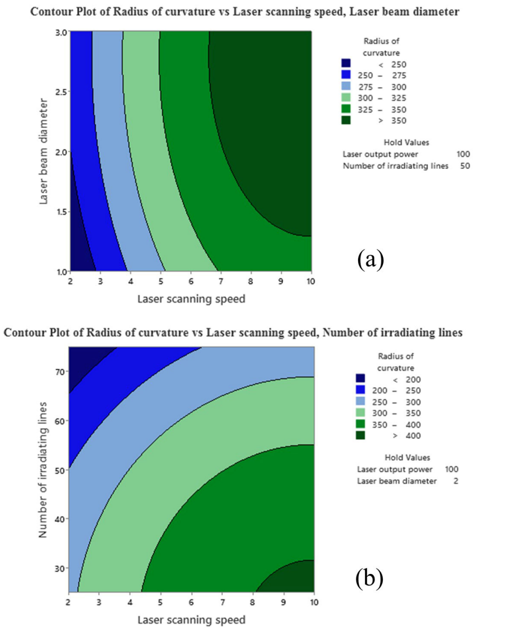

Fig. 6. Interactions between LSS and other parameters and their effects on the RC of the tube: (a) LSS - LBD, (b) LSS – NIL.

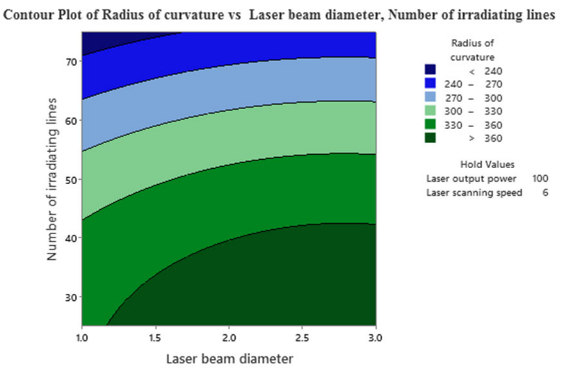

Fig. 7. Interaction between LBD and NIL and their effect on the RC of tube.

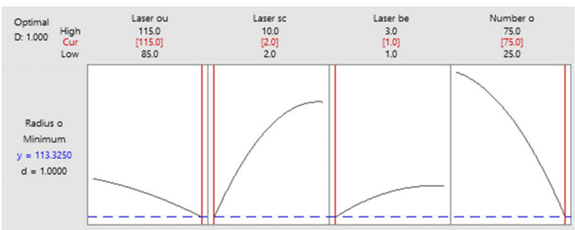

Fig. 8. Optimal conditions of input parameters to achieve the minimum RC value of the tube.

4. Conclusions

In this study, the laser forming process of tubes using an irradiation scheme with parallel straight lines was experimentally studied. The primary goal was the fabrication of a 3D tube from an initially straight tube using the proposed irradiation method. In addition, the effects of laser parameters such as LOP, LSS, LBD and NIL on the RC of laser formed tubes were examined. To conduct a comprehensive and precise analysis of both the individual effects and the interactions among the input parameters, the DOE method based on RSM was employed. In addition, statistical modeling and optimization techniques were used to deepen the understanding of how laser parameters affect RC. The following key findings were obtained:

- Experimental results confirmed that the proposed irradiation scheme successfully enabled the transformation of a straight tube into a 3D curved form.
- ANOVA results showed that all input laser parameters significantly influenced RC. Among them, NIL, LSS, LOP and LBD had the most substantial effect in that order.
- The coefficient of determination (R^2) for the RC prediction model was calculated to be 0.9981, indicating that the model could predict 99.81% of the experimental results accurately.
- An increase in LOP, led to a decrease in RC while increasing LSS resulted in an increased RC. In addition, increasing LBD raised the RC, whereas increasing NIL reduced it.
- Optimization analysis revealed that by setting LOP = 115 W, LSS = 2 mm/s, LBD = 1 mm, and NIL = 75, a minimum RC of 113 mm could be achieved.

Conflict of interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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5. References

[1] Kraus, J. (1997). Basic processes in laser bending of extrusions using the upsetting mechanism. In M. Geiger, & F. Vollertsen, (Eds.), *Laser assisted net shape engineering 2, Proceedings of the LANE'97* (Vol. 2, pp. 431–438). Meisenbach: Bamberg, Germany.

[2] Silve, S., Steen, W. M., & Podschier, B. (1998). Laser forming tubes: a discussion of principles. In *ICALEO*

'98: Proceedings of the Laser Materials Processing Conference (pp. 151–160). FL, USA. https://doi.org/10.2351/1.5059142

[3] Li, W., & Yao, Y. L. (2001). Laser bending of tubes: mechanism, analysis and prediction. *Journal of Manufacturing Science and Engineering, 123*(4), 674-681. https://doi.org/10.1115/1.1392992

[4] Hsieh, H. S., & Lin, J. (2005). Study of the buckling mechanism in laser tube forming. *Optics & Laser Technology*, *37*(5), 402-409. https://doi.org/10.1016/j.optlastec.2004.06.004

[5] Zhang, J., Cheng, P., Zhang, W., Graham, M., Jones, J., Jones, M., & Yao, Y. L. (2006). Effects of scanning schemes on laser tube bending. *Journal of Manufacturing Science and Engineering*, *128*(1), 20-33. https://doi.org/10.1115/1.2113047

[6] Guan, Y., Yuan, G., Sun, S., & Zhao, G. (2013). Process simulation and optimization of laser tube bending. *The International Journal of Advanced Manufacturing Technology, 65*, 333-342. https://doi.org/10.1007/s00170-012-4172-6

[7] Wang, X. Y., Wang, J., Xu, W. J., & Guo, D. M. (2014). Scanning path planning for laser bending of straight tube into curve tube. *Optics & Laser Technology, 56,* 43-51. https://doi.org/10.1016/j.optlastec.2013.07.001

[8] Jamil, M. C., Fauzi, E. I., Juinn, C. S., & Sheikh, M. A. (2015). Laser bending of pre-stressed thin-walled nickel micro-tubes. *Optics & Laser Technology, 73*, 105-117. https://doi.org/10.1016/j.optlastec.2015.04.012

[9] Imhan, K. I., Baharudin, B. T. H. T., Zakaria, A., Ismail, M. I. S. B., Alsabti, N. M. H., & Ahmad, A. K. (2017). Investigation of material specifications changes during laser tube bending and its influence on the modification and optimization of analytical modeling. *Optics & Laser Technology, 95*, 151-156. https://doi.org/10.1016/j.optlastec.2017.04.030

[10] Safari, M. (2020). A study on the laser tube bending process: effects of the irradiating length and the number of irradiating passes. *Iranian Journal of Materials Forming, 7*(1), 46-53. https://doi.org/10.22099/ijmf.2019.34213.1133

[11] Khandandel, S. E., Seyedkashi, S. H., & Moradi, M. (2020). A novel path strategy design for precise 2D and 3D laser tube forming process; experimental and numerical investigation. *Optik, 206*, 164302. https://doi.org/10.1016/j.ijleo.2020.164302

[12] Khadandel, S. E., Seyedkashi, S. M. H., & Hoseinpour Gollo, M. (020). Effect of cooling on bending angle and microstructure in laser tube bending with circumferential scanning. *Iranian Journal of Materials Forming, 7*(1), 14-23. https://doi.org/10.22099/ijmf.2019.34652.1137

[13] Keshtiara, M., Golabi, S. I., & Tarkesh Esfahani, R. (2021). Multi-objective optimization of stainless steel 304 tube laser forming process using GA. *Engineering with Computers, 37*, 155-171. https://doi.org/10.1007/s00366-019-00814-0