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Experimental Investigation of the Effects of Process Parameters on the Radius of Curvature in Laser Forming Process of Cylindrical Surfaces

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Abstract: In this work, the laser forming process of cylindrical surfaces is studied experimentally. For this purpose, the effects of process parameters such as laser power, laser scanning scheme, and distance between irradiation lines on the radius of curvature of the laser-formed cylindrical surfaces are examined. The design of experiment (DOE) method based on the Box–Behnken algorithm is also employed for investigations. To produce the cylindrical surfaces from flat sheets, parallel lines are used as the irradiation scheme. The results show that by increasing the laser power, the radius of curvature for a laser-formed cylindrical surface can be decreased. Additionally, the radius of curvature of the cylindrical surface increases when the scanning speed increases. In addition, it is concluded that the radius of curvature decreases when the distance between irradiation lines increases.

Keywords: laser forming process; cylindrical surface; radius of curvature; design of experiments

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1. Introduction

Laser forming is a noncontact process for the fabrication of 2D and 3D shapes from flat sheets without any mechanical tools. In this method, after irradiation sheet surface with a laser beam, a temperature gradient is created across the sheet thickness that leads to thermal strains in the sheet. Therefore, local plastic deformations are created in the sheet, and consequently, the sheet is bent. In recent years, much research has been reported about the laser forming process (LFP). Gisario et al. [1] investigated the three-dimensional LFP of stainless steel for the fabrication of dome shapes with different patterns. They concluded that by using tailored irradiating patterns, 3D shapes can be produced with a high-power diode laser. Safari and Farzin [2] implemented a spiral pattern for manufacturing a saddle-shaped surface from a flat sheet and successfully fabricated a saddle-shaped part. They also studied the effects of spiral pitch, a number of spiral passes, and movement patterns on the deformations of laser-formed saddle shapes. In another work, Safari et al. [3], using statistical analysis, studied the effects of process parameters such as spiral pitch, number of spiral passes, and movement patterns and their interactions with the deformations of a laser-formed saddle part and with the spiral irradiating scheme. They also optimized the deformations of the saddle-shaped part based on the statistical results. Hoseinpour Gollo et al. [4] applied various irradiating patterns for the fabrication of cap-shaped parts from a flat circular plate. They concluded that the spiral irradiating scheme can fabricate a cap-shaped part with a desired radius and edge distortions via LFP. Abolhasani et al. [5] investigated the effects of the beam diameter and hatch spacing between the scanning paths on the bendability of 3D laser-formed specimens. They also numerically studied the strains on heating lines to better understand the deformation mechanism. Navarrete et al. [6] compared the laser-formed 3D-shaped parts with single S-shaped, multiple circular, and single piecewise linear scanning paths. They also studied the fabrication of 3D-shaped parts with different laser parameters. Abolhasani et al. [7], using a double raster scanning pattern, studied the LFP of 3D shapes to obtain a laser-formed specimen with laser deformations after only one pass of laser irradiation. They found that the amounts of deformations were considerably dependent on the overlapping between the adjacent irradiating lines. Chakraborty et al. [8] numerically studied the mechanism of deformation in LFP of a bowl shape with a radial irradiating scheme. They concluded that the sheet is formed under shrinkage and local buckling around the irradiating paths. Safari and Mostaan [9] investigated the LFP of cylindrical surfaces with an arbitrary radius of curvature. They used simple linear irradiation paths for the fabrication of cylindrical surfaces. Additionally, they developed an analytical method for manufacturing cylindrical surfaces with an arbitrary radius of curvature.

Khandandel et al. [10] proposed a new method based on circular irradiating schemes for the fabrication of 2D and 3D shapes in a laser tube-forming process. The presented method was programmable so that different shapes could be formed by only changing the input parameters. Thomsen et al. [11] used a 2D laser scanner to measure the fabricated surface via the laser forming process. They verified the proposed method through an experimental case study. It was proved that the presented method can be used well in the laser forming process. Bucher et al. [12] studied the laser forming process of sandwich panels with metal foam cores. They analyzed the mechanisms of bending deformations during the laser irradiating process. They concluded that the established mechanisms for laser forming of solid metal and metal foam can also be used for sandwich panels. Masoudi Nejad et al. [13] investigated the laser bending process of two layered aluminum-copper sheets using the design of experiment method and finite element simulations. They proposed an improved irradiating scheme and concluded that the bending angle can be considerably increased. Mulay et al. [14] proposed an analytical method based on strain energy for the prediction of the bending angle in the laser bending process. In the proposed method, the temperature gradient is determined across the sheet thickness and, consequently, the thermal strains are computed. The effectiveness of the proposed analytical method was proved by confirming the results with experimental tests and also by comparing the results with those of other analytical methods. Wang et al. [15] studied the laser forming process for the fabrication of saddle- and bowl-shaped surfaces. Their investigation focused on changing the process parameters and irradiation paths. They concluded that non-uniform distribution of the temperature along the heating line is the basic factor in determining the accuracy of the laser forming process. Shen et al. [16] proposed a method for analyzing the laser forming process based on a minimum energy calculation and control of comprehensive strains. They fabricated the double-curvature surfaces based on the presented method and nonlinear deformation analysis. They verified the effectiveness of the proposed method with experimental tests. Shen et al. [17] studied the laser forming process of double-curvature surfaces of cylindrical sheets. They presented a strategy for determining the heating lines based on the optimization of strain energy using finite element simulations. The efficiency of the proposed technique was validated by the experimental tests. Measuring the temperature during the process, as well as checking the characteristics of the laser-processed surfaces, can greatly help to analyze the results of the laser material processing processes. This issue has been studied by some researchers in recent years [18–20], whose results can be useful for other researchers.

An examination of the literature shows that research on the LFP of cylindrical surfaces is very small, and due to the ability of lasers to produce these surfaces, further research on the LFP of cylindrical surfaces is necessary. Therefore, in this research, using the implemented pattern created by Safari and Mostaan [9], the effects of input process parameters such as laser power, scanning speed, and distance between irradiation lines on the radius of curvature of a laser-formed cylindrical surface is investigated with a statistical analysis. The effects of interactions between the input process parameters on the radius of curvature are also investigated.

2. Materials and Methods

The material used in this study is stainless steel 304 with dimensions of 1 mm (thickness) × 100 mm (length) × 60 mm (width). For LFP, a laser machine with a continuous wave (CW) laser beam and a maximum power of 120 watts is employed. To enhance the laser beam absorption, the surface of the sheets was covered with graphite powder. Three important process parameters were selected as influencing parameters, including laser power, scanning speed, and distance between irradiation lines. To find a proper range of input parameters, some trial-and-error experiments were performed. Table 1 shows the levels of the process parameters under which the current study was conducted.

Table 1. The levels of parameters for LFP of cylindrical surfaces.

Parameter	Symbol	Limits		
Laser power (watts)	P	36	72	108
Scanning speed (mm/s)	S	2	5	8
Distance between irradiation lines (mm)	D	2	4	6

In recent years, the response surface methodology (RSM) has been widely used in the analysis of processes related to laser-assisted material processing [21]. However, in this research, the RSM based on the Box–Behnken algorithm was used for the design of experiments. Therefore, a total of 15 experiments were carried out, and the list of them is available in Table 2.

Table 2. Executed experiments for LFP of cylindrical surfaces.

Sample	Laser Power	Scanning Speed	Distance between Irradiation Lines
1	72	5	4
2	72	8	2
3	72	2	6
4	36	2	4
5	108	8	4
6	72	5	4
7	36	8	4
8	72	5	4
9	36	5	6
10	108	5	6
11	108	5	2
12	108	2	4
13	36	5	2
14	72	2	2
15	72	8	6

In Figure 1, some of the laser-formed cylindrical surfaces obtained from LFP with different input parameters that lead to the fabrication of cylindrical surfaces with different radii of curvature are shown.

It should be noted that temperature measurements in a study similar to this research were carried out by the authors [9] in a scientific and accurate way.

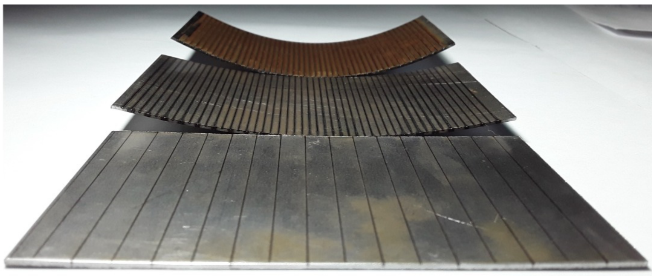

Figure 1. Some of the laser-formed cylindrical surfaces from primary sheets with dimensions of 1 mm (thickness) × 100 mm (length) × 60 mm (width), obtained from different input parameters.

3. Results and Discussion

In this section, first, the results of the analysis of variance (ANOVA) for the radius of curvature of laser-formed cylindrical surfaces are presented in Table 3.

Table 3. The results of analysis of variance (ANOVA) for the radius of curvature of laser-formed cylindrical surfaces.

Source	DF	Adj SS	Adj MS	F-Value	*p*-Value
Model	7	1,350,272	192,896	255.84	0.000
Linear	3	1,090,664	363,555	482.19	0.000
P	1	396,437	396,437	525.80	0.000
S	1	267,143	267,143	354.32	0.000
D	1	427,085	427,085	566.45	0.000
Square	2	124,750	62,375	82.73	0.000
P × P	1	104,382	104,382	138.44	0.000
S × S	1	14,226	14,226	18.87	0.003
Two-way Interaction	2	134,858	67,429	89.43	0.000
P × D	1	96,074	96,074	127.43	0.000
S × D	1	38,784	38,784	51.44	0.000
Error	7	5278	754		
Lack of Fit	5	5278	1056		0.127
Pure Error	2	0	0		
Total	14	1,355,550			

In the present study, the ANOVA was performed with a reliability of 95%; therefore, the input parameters with a p-value less than 0.05 are effective parameters for the radius of curvature of cylindrical surfaces. It can be concluded from Table 3 that laser power, scanning speed, the distance between irradiation lines, the square of laser power, the square of laser speed, the interaction between laser power and distance between irradiation lines, and the interaction between laser speed and distance between irradiation lines are effective with regard to the radius of curvature.

The prediction equation for the radius of curvature based on the results of the statistical analysis is shown in Equation (1).

$$\text{Radius of curvature (mm)} = 348.5 - 16.20\,P + 64.0\,S + 188.4\,D + 0.1294\,P \times P - 6.88\,S \times S - 2.152\,P \times D + 16.41\,S \times D \quad (1)$$

The values of R-sq = 99.61%, R-sq (pred) = 99.22%, and R-sq (adj) = 97.42% show that the employed model can accurately predict the behavior of the radius of curvature of laser-formed cylindrical surfaces. The residual plots for the applied model are shown in Figure 2, and it is concluded from Figure 2 that the applied model can predict the output parameter with acceptable accuracy.

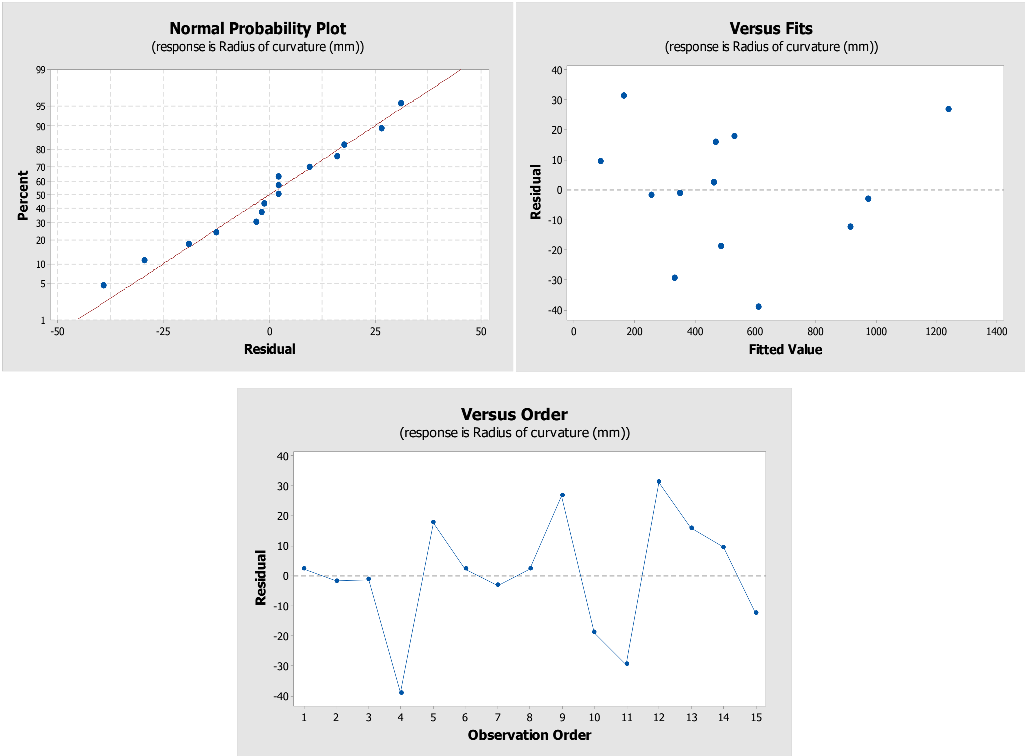

Figure 2. Normal probability plots for radius of curvature.

In Figure 3, the effects of laser power, scanning speed, and distance between irradiation lines on the radius of curvature of laser-formed cylindrical surfaces are shown. As is seen from Figure 3, the radius of curvature decreases as the laser power increases. The reason is that as the laser power increases, the heat irradiating into the sheet also increases. Therefore, the number of thermal strains in the sheet increases, which leads to an increase in the plastic areas in the sheet. However, as the deformations of the sheet increase, the radius of curvature of the laser-formed cylindrical surface decreases. In addition, it can be concluded from Figure 3 that the radius of curvature of laser-formed cylindrical surfaces increases as the scanning speed increases. This is because, with an increase in the scanning speed, there is not enough time for the thermal energy of the laser to enter the sheet, and as a result, thermal strains and the number of plastic deformation areas are reduced. Finally, the radius of curvature increases by reducing the amount of deformation in the sheet. It is also proven from Figure 3 that the radius of curvature of laser-formed cylindrical surfaces increases as the distance between the irradiation lines increase. The reason for this is clear. By increasing the distance between the irradiation lines, the number of laser beam irradiation paths on the sheet is reduced, which leads to a decrease in the amount of thermal energy that enters into the sheet, and finally, leads to an increase in the radius of curvature.

Next, the interaction between the input parameters and its effect on the radius of curvature of laser-formed cylindrical surfaces is investigated. In Figure 4, the interaction between laser power and distance between irradiation lines on the radius of curvature is shown. As can be seen from Figure 4, the radius of curvature of laser-formed cylindrical surfaces decreases as laser power increases and as the distance between irradiation lines decreases. The reason for this, as mentioned earlier, is that there is an increase in the amount of laser heat that is inputted to the sheet, which is followed by an increase in the areas of plastic deformation, and which ultimately leads to an increase in the deformation of the sheet and a decrease in its radius of curvature.

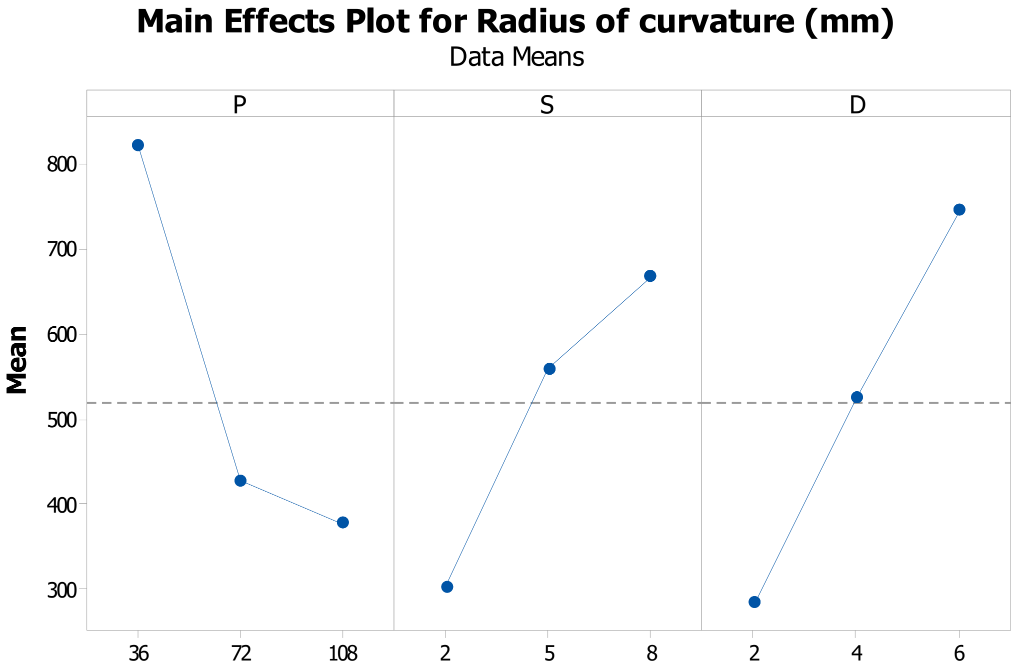

Figure 3. The effects of input parameters on the radius of curvature of laser-formed cylindrical surfaces.

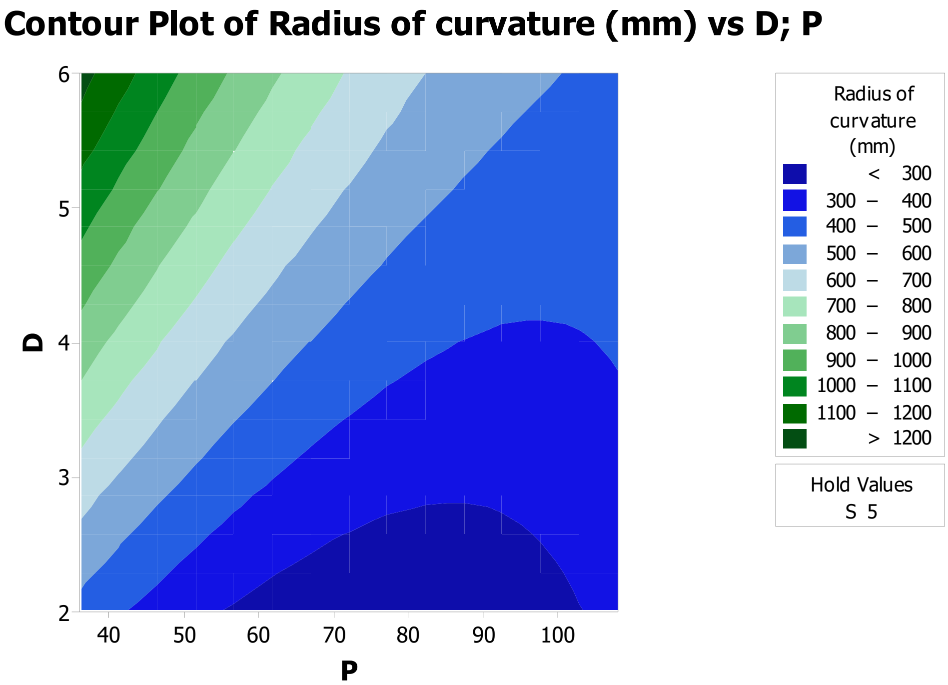

Figure 4. The interaction between laser power and distance between irradiation lines on the radius of curvature.

In Figure 5, the interaction between scanning speed and distance between irradiation lines on the radius of curvature is shown.

In Figure 5, it is proven that the simultaneous reduction in the scanning speed and the distance between the irradiation lines significantly reduces the radius of curvature. The reason for this issue is, again, the increase in the amount of thermal energy from the laser applied to the sheet.

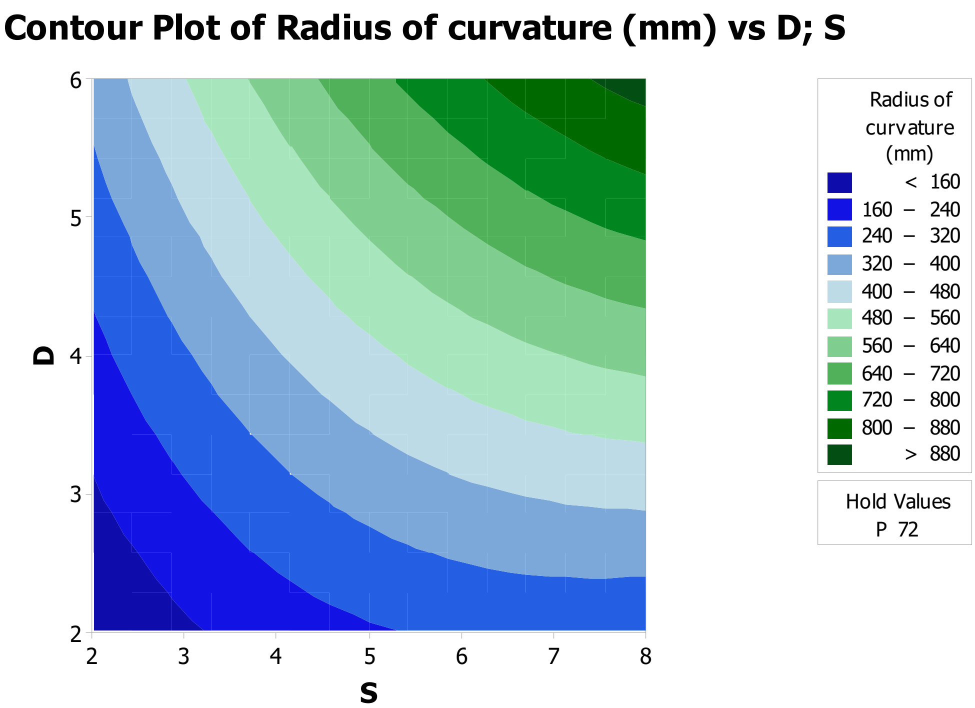

Figure 5. The interaction between scanning speed and distance between irradiation lines on the radius of curvature.

4. Conclusions

In this work, the effects of laser power, scanning speed, and distance between irradiation lines on the radius of curvature of laser-formed cylindrical surfaces were experimentally studied. In the investigations carried out in this research, the design of experiment method based on the Box–Behnken algorithm was used. Additionally, the effect of the input parameters on the radius of curvature was analyzed using statistical analysis. Finally, the following results were obtained from this research:

- It was concluded that laser power, scanning speed, the distance between irradiation lines, the square of laser power, the square of laser speed, the interaction between laser power and distance between irradiation lines, and the interaction between laser speed and distance between irradiation lines are effective with regard to the radius of curvature of laser-formed cylindrical surfaces.
- The reliability index (R-sq) showed that the employed model in this research could accurately predict the behavior of the radius of curvature of laser-formed cylindrical surfaces.
- It was deduced that the radius of curvature decreases as the laser power increases. The reason is that by increasing the laser power, the amount of irradiated heat applied to the sheet is increased. Therefore, the number of thermal strains in the sheet is increased, which leads to an increase in the plastic areas in the sheet.
- It was concluded from the obtained results that the radius of curvature of laser-formed cylindrical surfaces increases as the scanning speed increases. The reason is that by increasing the scanning speed, there is not enough time for the thermal energy of the laser to enter the sheet, and as a result, thermal strains and the number of plastic deformation areas were reduced. Finally, the radius of curvature increases by reducing the amount of deformation of the sheet.
- It was proven that the radius of curvature of laser-formed cylindrical surfaces increases as the distance between the irradiation lines increases. The reason is that by increasing the distance between the irradiation lines, the number of laser beam irradiation paths on the sheet is reduced, which leads to a decrease in the amount of thermal energy that enters the sheet and, finally, leads to an increase in the radius of curvature.

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