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Parametric Study of Laser Drilling Process Using Multi Variable Regression Analysis

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Abstract

The laser drilling process is an advanced manufacturing technique extensively employed for intricate and high-value components in aerospace, automotive, and electronics industries. Laser drilling technology offers opportunities to meet the contemporary demands of industries using a broad spectrum of engineering materials. However, this process encounters several engineering challenges such as thermal damage, dimensional inaccuracies, and the formation of a recast layer in the drilled components. This study focuses on examining how key process parameters—assist gas pressure, current, stand-off distance, and trepanning speed—affect the thickness of the recast layer in the super alloy Inconel-718. The Design of Experiments methodology is utilized for conducting the experimental work, specifically choosing the Box-Behnken design for the necessary experiments. Following the experimental procedure, the thickness of the recast layer for each drilled hole is measured using Scanning Electron Microscopy (SEM) at IIT Kanpur. The collected measurements are then used to create a multivariable regression model to analyze the impact of the process parameters on recast layer thickness. The generated model showed a strong statistical fit for predicting recast layer thickness in laser trepan drilling, evidenced by an Adjusted R-square of 82%. After examining the developed contour and 3D plots, optimal ranges for the process parameters have been established as follows: assist gas pressure between 7–8 bar, current between 250–260 A, stand-off distance of 1.5–1.6 mm, and trepanning speed of 40–55 mm/min.

Keywords: Laser trepan drilling, inconel-718, regression analysis, scanning electron microscopy, dimensional

INTRODUCTION

Laser machining process is modern manufacturing process be adopted for complex and precise manufacturing in advanced technical requirement.

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This process is able to produces complexes geometry in wide range of engineering material. Uses of this process extended to many engineering application such as aerospace, automotive, and electronics. Basic principal of laser drilling is in four stages [1]

1. The absorption of laser energy,
2. Heating of the material,
3. Vaporization and cooling
4. Removal of molten material from drilling zone.

Outcome of this process depends on the many input factors and types of laser material being used such solid-state lasers, CO_2, fiber.

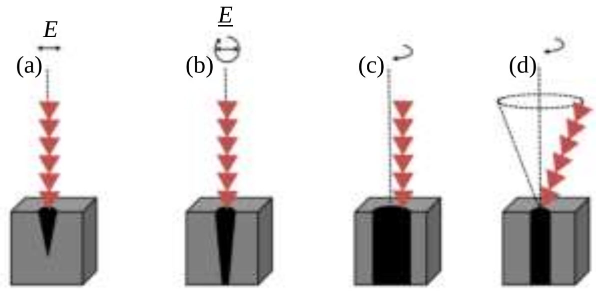


Figure 1. Schematic diagram of laser drilling methods [2].

Many advantages of using laser drilling in modern manufacturing; however laser drilling faces significant challenges, thermal damages, dimensional precision and formation of a recast layer. Recast layer thickness is thickness of re-solidified with parent metal, which exhibits the poor performances during application of laser drilled parts.

Researchers are improving the laser drilling process using different methodology and techniques. Poor efficiency and poor quality still the issues researchers and industry dealing with. However, the integration of data science and machine learning into laser drilling processes represents promising path.ML and data science tool can perform the real time modeling and optimization of the laser process parameters for understanding and improving the process for more sophisticated and challenging applications.

Machine learning and data science tools are being incorporated by different researcher for improving the laser drilling process. Experimental study and advanced computational methods are producing the promising results in improvement of laser drilling process. Researchers are gaining deep inside understanding of laser process using the experimental data and advanced computational tools.

In this study a experimental works is conducted on nickel based alloy Inconel-718, which is extensively used for aerospace parts manufacturing, gas turbine components, medical equipment. Box behnken Design of experiments is sued for conducting the experimental work. Current, Assistant gas pressure, standoff distance and trepanning speed are taken as input process parameters. Thickness of recast layer is measured for each drilling hole using SEM facility available at IIT Kanpur. Figure shows the schematic diagram of laser drilling experimental setup. Figure 1 shows the different scheme of laser drilling operations.

LITERATURE REVIEW

Laser machining have attracted the researchers around the world to make is more efficient and useful for industrial manufacturing. Laser machining produces the parts with extra ordinary accuracy and can machine the wide range of engineering material.

Current available research in laser drilling highlights different methods and approach for drilling and machine of different material. Laser drilling also integrated with other process to make more useful for industrial application.

There are the major approach exits for laser drilling that [3–7]

1. Percussion drilling
2. Trepan drilling
3. Helical drilling

In percussion drilling, laser beam directly impended to work material without any relative motion between work material and laser beam. Laser beam is impended in pulses form to control the heating and properly removal of molten material the work piece. Despite of many advantages of percussion drilling, there are disadvantage associated with the laser percussion drilling as follows [8–10]:

1. Limited hole size
2. Poor control of laser material interaction
3. Poor dimensional stability
4. Distorted geometry

Different researchers have tried the different method to understand the laser drilling. Subasi et.al [11] studied the water jet-guided laser micro-hole drilling advanced alloy. Using water jet for cooling the drilling area author able to reduce the recast layer formation and other thermal dames. Similar study conducted by Zhang et al. [12], they have studied the using water assistance, found that addition of water improves overall hole quality and reduces the heat affected zone in material stainless steel. This study highlights benefits of using cooling water in laser processes.

Meng Li et al. [9] have used femtosecond laser drilling on nickel base supper alloy. improved quality of drilling hole for film cooling have developed in nickel-based super alloys for turbine blades using helical drilling. Tao et al. [13] have improved the hole characteristic in thick carbon fiber-reinforced polymer laminates by using a laser-mechanical compound drilling method.

Changlong et al. [14] have used water-assisted method to reduce the heat accumulation in ultrafast laser drilling. Hey have studied underwater drilling with low pulse energy, capturing laser-induced plasma (LIP) and comparing material removal in air and water. Authors have developed a numerical model the predicts hole size.

The features of laser drilled holes are influenced by the path design of laser systems. Ai et al. [15] studied the surface quality characteristics of micro-holes drilled in Ti-6Al-4V using short pulse lasers.. Their research underscored the importance of machining parameters in maintaining mechanical properties, emphasizing the need for carful process design in high-performance applications. Laser trepanning processes is shown in the Figure 2.

Tamil Alagan et al. [17] investigated the drilling quality of Al-CFRP stacks with innovative techniques. Author have optimized drilling parameters to reduced delamination and improved hole quality. This study offers enhancing drilling efficiency in composite-metal stacks.

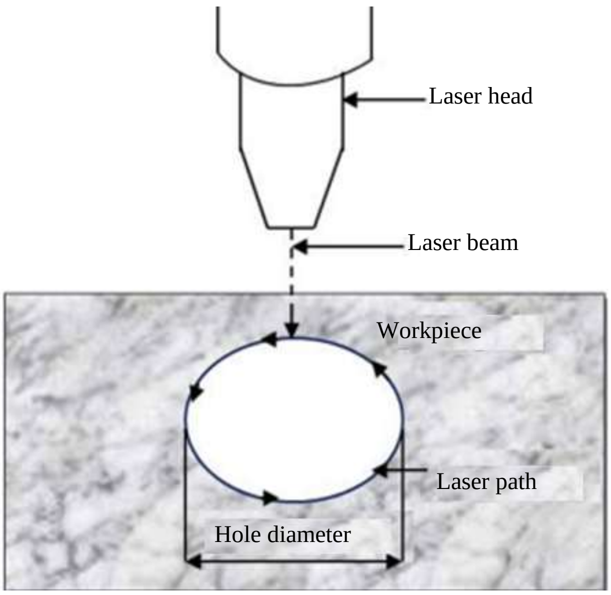


Figure 2. Schematic of laser trepan drilling [16].

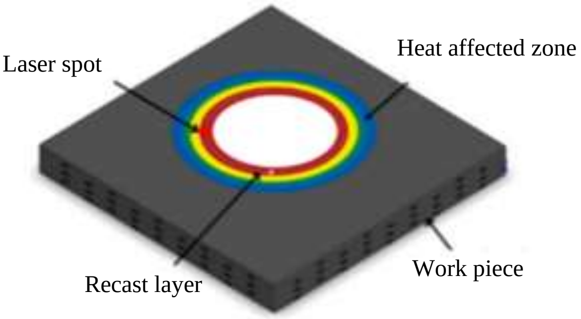


Figure 3. Recast layer [18].

The thickness of the recast layer of Zirconia Toughened Alumina (ZTA) ceramic after laser drilling utilizing the trepanning process was studied by Surendra Kumar et al. [16]. Author studied Their study sought to determine the effects of several process variables on the recast layer's production, including assist gas pressure, trepanning speed, pulse width, and pulse time. According to the study, a thicker recast layer resulted from increasing the pulse width. This is due to the fact that a longer pulse duration gives the heat more time to interact with the material, which causes a higher degree of melting and recasting. On the other hand, the authors found inconsistent results regarding the impact of pulse frequency on the thickness of the recast layer.

Authors suggested that moderate pulse frequency is better for reduced recast layer thickness, and increasing the trepanning speed leads to increase in recast layer thickness. However, higher assist gas pressure reduced the recast layer thickness, likely by improving cooling. Overall, the study highlighted the importance of optimizing laser drilling parameters to control recast layer formation in ZTA ceramics and achieve desired material properties.

Technological application and stress application, recast layer formed during laser drilling is very crucial in determining the required mechanical properties and stability of drilled parts during. In this review work, formation of recast layer, modeling and process optimization of has have been reviewed. Recent research on their development, behavior, and consequences in a variety of materials are reviewed. Figure 3 below shows the recast later layer during drilling.

From review of literature it is found that recast layer formation in laser drilled part is very severe, formation of recast layer is caused by re solidification of molten material. During laser drilling substantial heat is produced, temperature reaches beyond melting temperature. Molten material must to be removed from the drilling zone immediately after getting melted, and if immediately removal is not here than molten material cooled down and re solidified with parent metal.

Literature review of laser drilling and recast layer formation indicates the relationship between process parameters and laser drilling quality characteristics. Studied reported in literature that recast layer thickness and its formation is affected by many process parameters such as current, assist gas pressure, focal distance, MRR, pulse width, and pulse time. For reducing the thermal damages and improving the surface integrity, interactive parameters effects to be controlled by advances in laser machining processes, such as the trepanning method for drilling.

Laser drilling is advanced machining process, control of heat generated causes the thermal damages which ultimately results in formation of recast layer thickness and heat affected zone.

The research study is being conducted with the following objectives:

a. Understanding the processes that lead to recast layer formation.
b. Development of a predictive model for recast layer thickness.
c. Parametric study of laser drilling processes.

Table 1. Laser process parameter and their level.

Symbol	Parameter	Unit	Level-1	Level-2	Level-3
A	Assist gas pressure	bar	5	7	9
B	Current	Amp	180	220	260
C	Standoff distance	mm	1	1.4	1.8
D	Trepanning speed	mm/min.	15	35	55

EXPERIMENTAL AND MEASUREMENT WORK

Material and Properties

For quality characterization in laser trepanning, experimental work is planned as per Box Behnken design of experiments. For performing the experimental work, Inconel-718 sheet with 1.4mm thickness is procured from Randhir Metal Ltd. in Mumbai.

Process Parameters and Levels

One of the most important quality characteristics in laser drilling is the thickness of the recast layer. The range and level of the four important process parameters that have been found to affect the development of the recast layer are listed in the Table 1.

Design of Experiments and Experimentation

A Box-Behnken design (BBD) is experimental technique for examining the different process modeling. BBD requires three levels of each parameters being studied: Every level of parameter is leveled as low (-1), middle (0), and high (+1), which stand for lowest, nominal, and maximum values. These levels form the design, any one process parameter kept at level of medium and other parameter are kept at two extreme value of similar for both. This facilitates an effective investigation of the parameter space and aids in determining the elements interaction.

Number of Runs and Experimental Setup: Total number of experimental runs required as per BBD of experimental work can be found by following mathematical relationship:

$$N=2k(k-1)+C \qquad (1)$$

Where,
N= Total number of experimental runs,
k = Number of factors,
C= No. Central point considered in design

In this study four process parameter (Factors) as: Current, Assist gas pressure, Trepanning speed, and Standoff distance are considered. Three central points are also considering in design of experiments to capture the inherent variability and guarantee experiment robustness. The formula is used to get the total number of runs:

$N=2\times4\times(4-1)+3=27$ runs

Therefore, there will be a total of 27 experimental runs for a design with 4 factors and 3 center points. These 27 experimental runs capture the effects of process parameters and recast layer formation in laser trepanning of Inconle-718. BBD design table is shown in Table 2.

Experimental Setup

250W maximum power laser drilling system, in which laser drilling nozzle moves in a circular motion using a CNC-controlled mechanism. By concentrating high-energy laser beams impends on work material to melt or evaporate the material, this arrangement enables the accurate and automated drilling of holes or patterns in a variety of materials. DOE table shown in Table 5.

- *Material used:* Inconel-718 sheet of 1.4 mm thick is purchased from Mumbai's Randhir Metal Ltd.

- *Laser equipment:* A solid state laser with a maximum power of 250w max power is used.
- *Parameters considered are:* current, assist gas pressure, standoff distance, trepan speed.
- *Assist gas:* Compressed air is used in experimentation.
- *CNC condoled:* 2mm hole is drilling using CNC program regulates the laser beam interface with the work material.
- *Filler gauges:* Varying sizes are used to adjust the standoff distance.

Measurement of Recast Layer Thickness

Following steps are following for taking SEM images of Laser drilled parts using SEM system model JSM-6010LA at IIT Kanpur,

- *Prepare samples for SEM observation:* Samples are prepared in 8×8 mm in size with precautions to study the recast layer thickness in SEM images. SEM image are captured at different magnifying range from 25–200.
- *Measure required diameters:* Drilling is performed for 2 mm diameter the hole. Measure d1 and d2, which represent the diameters at two distinct points on the recast layer's boundary as shown in Figure 4. SEM images are shown in Figure 5.
- *Calculate the thickness:* Substitute the measured values into the mathematical relationship formula for recast layer thickness. Recast layer thickness can be found.

Table 2. DOE table for experimental work.

S.N.	Assist gas pressure (bar), A	current (Amp), B	Stand-off distance (mm), C	Trepanning speed (mm/min), D
1	1	0	1	0
2	0	0	1	-1
3	-1	0	-1	0
4	0	1	1	0
5	-1	0	0	1
6	1	0	-1	0
7	1	0	0	-1
8	0	0	0	0
9	0	1	-1	0
10	-1	0	1	0
11	0	0	-1	-1
12	0	1	0	-1
13	0	-1	0	1
14	1	-1	0	0
15	1	0	0	1
16	0	1	0	1
17	1	1	0	0
18	0	0	0	0
19	-1	1	0	0
20	-1	0	0	-1
21	0	-1	1	0
22	0	0	1	1
23	0	-1	0	-1
24	0	0	0	0
25	0	0	-1	1
26	-1	-1	0	0
27	0	-1	-1	0

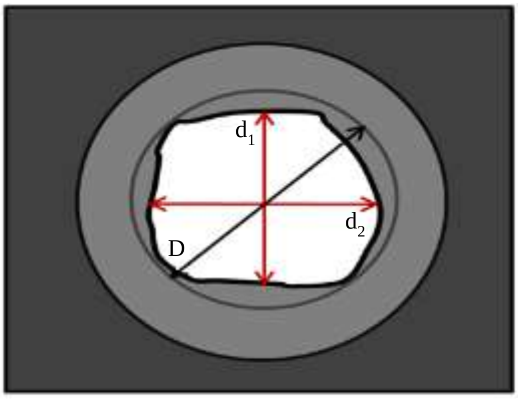


Figure 4. Measurement scheme of recast layer thickness.

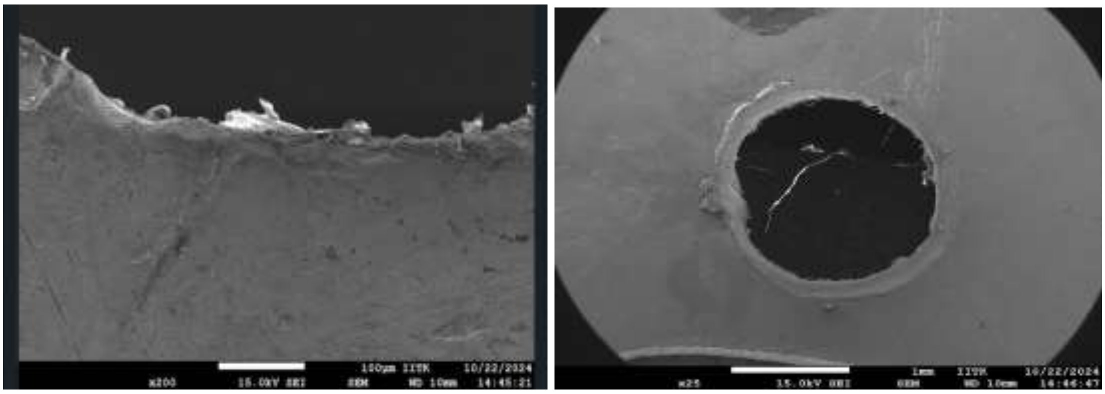


Figure 5. SEM images of drilled hole for 16th no. of experiments.

$$\text{Recast layer thickness} = \frac{(D-\frac{(d_1+d_2)}{2})}{2} \quad (2)$$

MODELING OF RECAST LAYER THICKNESS

To study the complicated relationship in process parameters and recast layer thickness, a multivariate quadratic regression model is developed. This quadratic model includes linear as well as nonlinear quadratic terms in model for capturing the interactive effect of process parameters.

Regression Model

Present study focuses on the understating of interactive effect of process parameters on formation of recast layer during laser trepan drilling of aerospace material sheet. For the said purpose, a multivariate quadratic regression model is a proven choice. Quadratic terms in the regression model explain the following phenomena of recast layer formulation.

Generalized multi variable quadratic regression model [19–20]:

$$Y = \beta_0 + \sum \beta_i * x_i + \sum(\beta_{ii} * x_{ii}^2) + \sum\sum \beta_{ij} * x_i * x_j + \mathcal{E} \quad (3)$$

Where,
β_0=Represents the intercept,
β_i= The linear effects,
β_ii= The quadratic effects,
β_ij= The interaction effects
E = The error term.
x = Process variables (Independent variables)

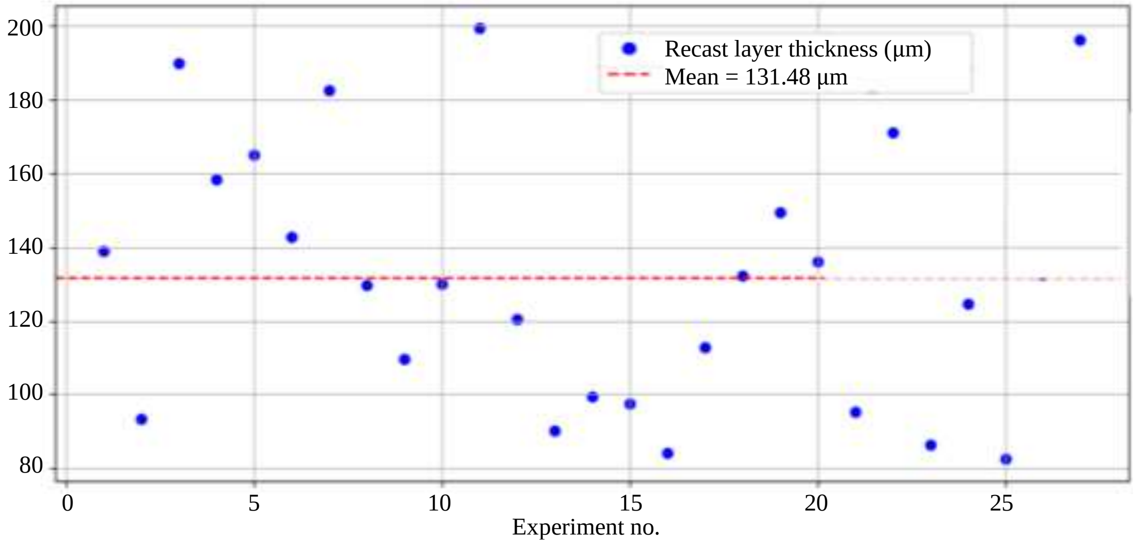


Figure 6. Experimental measured values of recast layer thickness.

This model structure enables the analysis of both individual parameter effects and their combined influence on the response variable."

Multi variable quadratic regression model are developed using Minitab soft ware. Experimental data as shown in Figure 6 is taken for developing the regression model.

Developed multi variable quadratic regression model:

Recast layer thickness,

$$t = 951 - 49.4\ A + 1.94\ B - 1178\ C + 0.06\ D + 3.33\ A^2 - 0.0105\ B^2 + 107\ C^2 - 0.0192\ D^2 - 0.0102\ AB + 17.6\ AC - 0.711\ AD + 2.34\ BC - 0.0126\ BD + 6.08\ CD \quad (4)$$

Developed regression model is checked for statistically significance. Regression model demonstrates a strong fit. Model explains 91.4% variation in recast layer thickness (t) with an adjusted R^2 of 82%. These statistical parameters, shows are reliability of developed regression model which captures effective prediction of process behaviors and parameters interactions. Further, ANOVA table is also developed for the regression model which contents the statistical parameters such F-value, P-Values, errors and degree of freedom. $F = 9.45$ and $p < 0.0001$ of the model explain variability (sum of square error) 30278.3 out of 33023.7 of the total variability. ANOVA shows that only 2745.5 variability due to errors in prediction. Table 3 and Table 4 shows ANOVA tables.

Interactive Effect of Process Parameters

3D plots and contour plots are created by using quadratic egression equation of recast layer thickness with the help of python plots library. These plots are helpful to understand the underlying interactive effects and variations. This study is very useful for understanding the recast layer formulations in challenging materials like Inconel-718. Process parameters, Assistant gas pressure, Current, Stand-off distance and trepanning speed play crucial role in recast layer formulations. Assistant gas pressure helps in removing the molten material from the drilling zone and immediately removal of molten material from the drilling zone affects the recast layer thickness, so increasing gas pressure may help in immediately removal of molten material while higher gas pressure also creates the rapid cooling of molten material due to forced convection heat loss from the drilling zone. Current provides the heat energy required for melting the work material in localized zone. Stand-off distance is distance between top surface of work material and bottom most surface of laser delivery nozzle, changing this distance infancies the focus length of laser beam, which is important for localized melting and removal of molten metal from the drilling zone.

Table 3. ANOVA Table (R-squrae: 91.2 % and Adjusted R-square: 82.0 %).

Source	DF	SS	MS	F	P
Regression	14	30278.3	2162.7	9.45	0.00001
Regression Error	12	2745.5	228.8		
Total	26	33023.7			

Table 4. Regression models coefficients and P values.

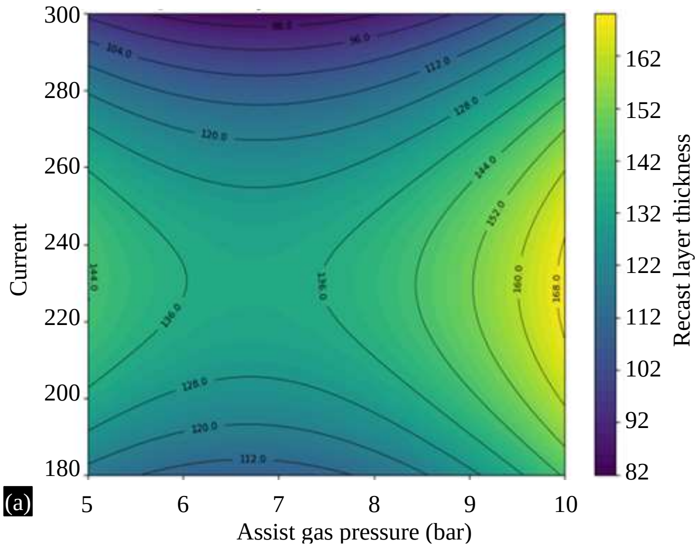
Predictor	Coef	SE Coef	T	P
Constant	951.500	374.400	2.540	0.026
A	-49.430	34.380	-1.440	0.176
B	1.941	2.059	0.940	0.365
C	-1178.100	171.900	-6.850	0.000
D	0.060	3.032	0.020	0.984
A2	3.328	1.637	2.030	0.065
B2	-0.011	0.004	-2.570	0.025
C2	107.220	40.940	2.620	0.022
D2	-0.019	0.016	-1.170	0.264
AB	-0.010	0.095	-0.110	0.916
AC	17.572	9.454	1.860	0.088
AD	-0.711	0.189	-3.760	0.003
BC	2.338	0.473	4.950	0.000
BD	-0.013	0.009	-1.340	0.206
CD	6.077	0.945	6.430	0.000

Trepanning speed limits the interaction time of laser beam and work material at higher speed. By understanding and controlling these interactions, manufacturers can achieve minimal recast layer thickness, improved surface quality, and enhanced overall machining efficiency, which are essential for a broad range of industrial application.

Interaction effect of assist gas pressure and current is shown in Figure 7. Medium assist gas pressure in range taken for analysis, typically around 6–8 bar facilitates the controlled removal of molten material. Simultaneously, operating at lower current values, such as 180–200 A restrict the heat energy input to work material, limiting the amount of molten material generated during the process. Similarity higher current 260 A provided the better opportunity with higher assist gas pressure for proper removal of material from the drilling zone, ensures a thinner recast layer, thereby enhancing surface quality and minimizing defects.

The Figure 8 indicates the interaction effects of assist gas pressure and stand –off distance on recast layer thickness. The 3D surface plot and contour plot indicates that recast layer thickness follows a parabolic trend with stand-off distance. Favorable range of these parameter for reduced recast layer thickness is Assist gas pressure = 5- 8 bar and stand-off distance= 1.4 – 2 mm. Shorter value of stand-off distance laser beam energy density focus may beyond the work material (outside of material thickness) causes poor melting.

By analyzing the contour plots and 3D plots Figure 9, of interactive effects of assist gas pressure and trepanning speed, it is found that thinner recast layer (below 80 μm) is achieved at higher trepanning speeds (55–60 mm/min) and elevated assist gas pressures (9–10 bar), as indicated by the darker regions plots. Higher assist gas pressure create favorable condition for proper removal of molten material from drilling zone while elevated trepanning speed restrict the interaction time between laser beam and work material which ultimately minimizing the thermal damages in drilling zone. Therefore, the optimal combination of 9–10 bar gas pressure and 55–60 mm/min trepanning speed is recommended to minimize the recast layer thickness and improve the quality of drilled holes.



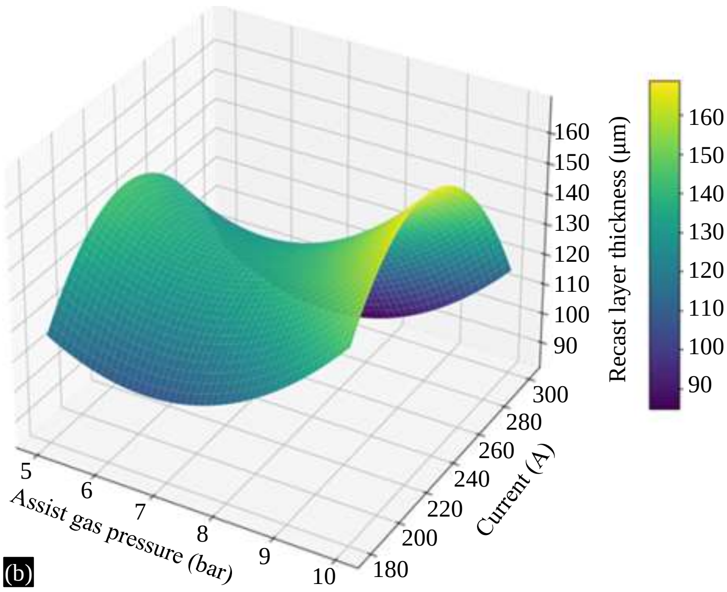
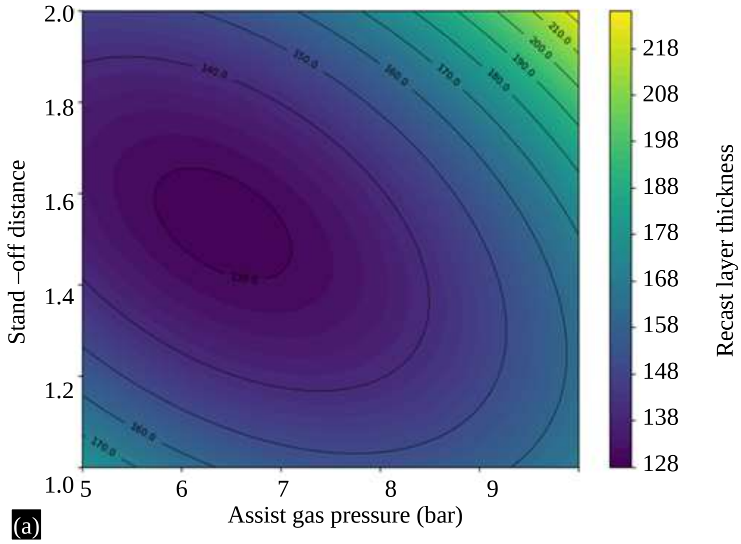
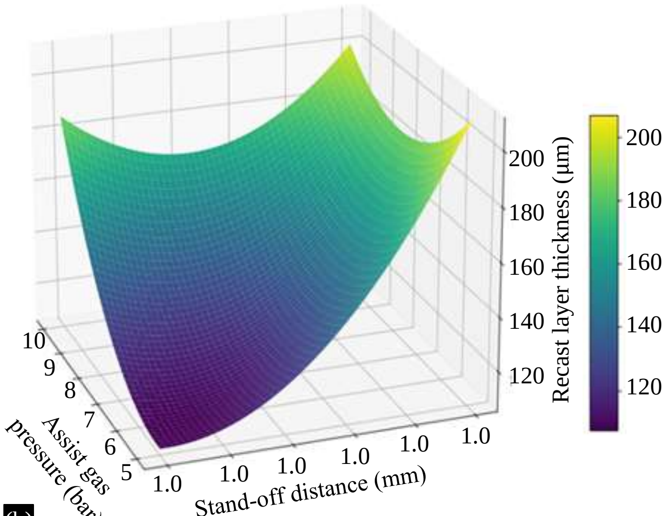


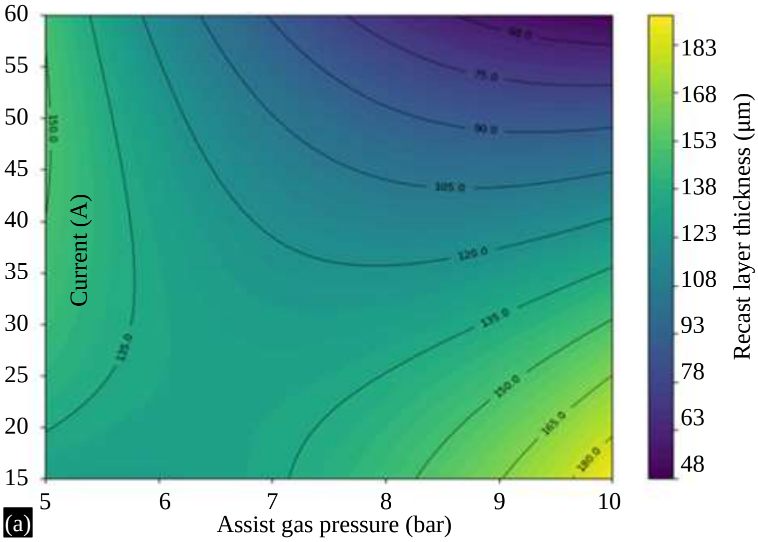
Figure 7. (a) and (b) Interactive effect of assist gas pressure and current.



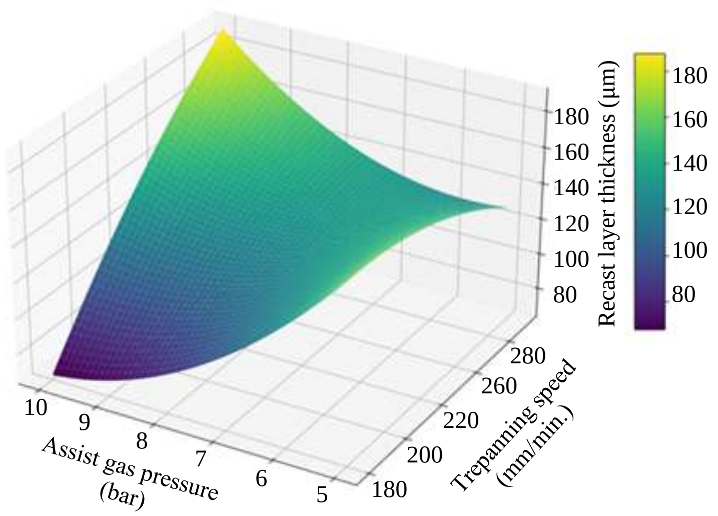


(b)

Figure 8. (a) and (b) Interactive effect of assist gas pressure and Stand-off distance.



(a)



(b)

Figure 9. (a) and (b) Interactive effect of assist gas pressure and trepanning speed.

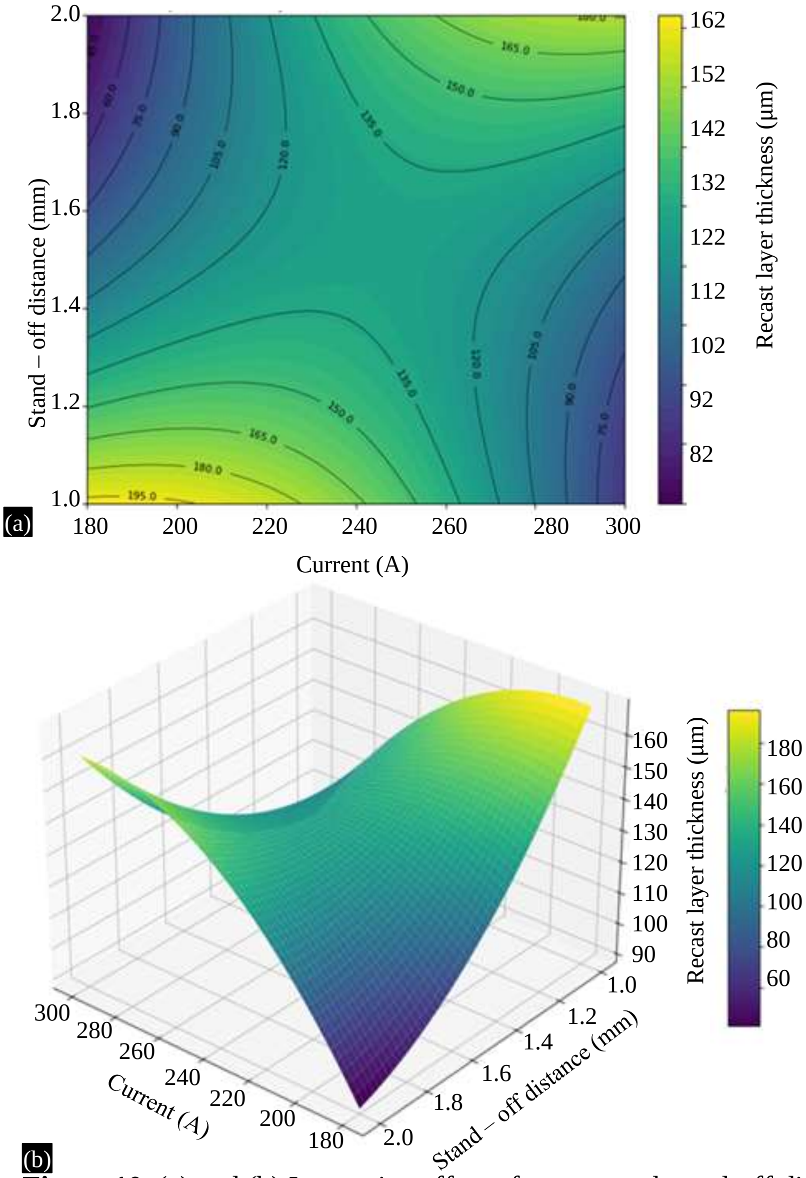


Figure 10. (a) and (b) Interactive effect of current and stand-off distance.

Figure 10 shows the combined effect of stand-off distance and current on formulation recast layer. Trend shows the two types of pattern in recast layer formation , first one that higher current (280–300 A) with lower stand-off distance (1–1.2 mm) and second is that lower current (180–200 A) with higher stand–off distance (1.6–2.0 mm) are favorable for thinner recast layer in laser trepan drilling of Inconel-718. These trends are due to facts that low heat dissipation ability, Inconel-718 tends to retain heat in the machining zone, leading to thicker recast layers if process parameters are not optimized. elevated currents (above 280 A) generate excessive heat, and higher stand-off distances (above 2.0 mm) reduce laser intensity on the surface, both resulting in thicker recast layers (above 120 µm). Therefore, careful control of the energy input and laser focus is critical, to minimize the recast layer thickness and enhance machining quality.

Figure 11 shows the combined effect of trepanning speed and current on formulation recast layer. Significant thermal interactions affected by the characteristics of the material are shown by analyzing the effect of current (A) and trepanning speed (mm/min) on the recast layer thickness (µm) during laser trepan drilling of Inconel 718. Inconel 718 is wknown for its high melting point (1260–1336°C) and poor thermal conductivity (11.4 W/m•K), which result in heat accumulation rather than dissipation in the machining zone. At higher currents (e.g., 240–300 A) and higher trepanning speeds (above 50 mm/min), the recast layer thickness is minimum. While lower trepanning speed combing with current range of 220–260 A produces thicker recast layer.

Figure 12 shows the combined effect of trepanning speed and stand-off distance on formulation recast layer. The study of how stand-off distance (SOD) and trepanning speed affect the thickness of the recast layer in laser trepan drilling of Inconel-718 reveals important patterns impacted by the low heat conductivity of the material. The high energy density of the laser beam results in excessive localized heating and slower cooling for low SOD values (1.0–1.4 mm), producing thick recast layers that is larger than 200 µm.

Favorable Range of Process Parameters

After careful study contour plots and process parameters range of Favorable process parameter have been established and indicated in Table 5. Range of process parameter is analyzed using the contour plots and favorable range is mentioned for every combination of parameters.

Table 5. Favorable range of process parameter.

Assist gas pressure (bar)	Current (A)	Stand-off distance (mm)	Trepanning speed (mm/min.
7–8	250–260	1.5–1.6	40–55

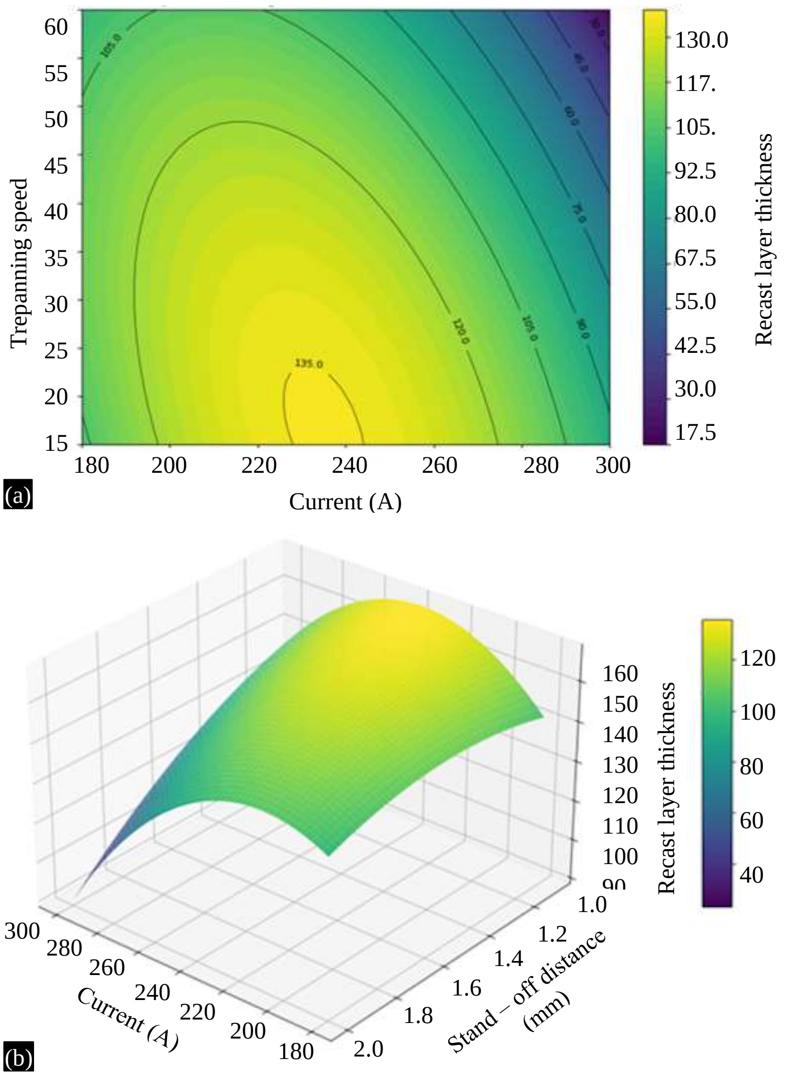


Figure 11. (a) and (b) Interactive effect of current and trepanning speed.

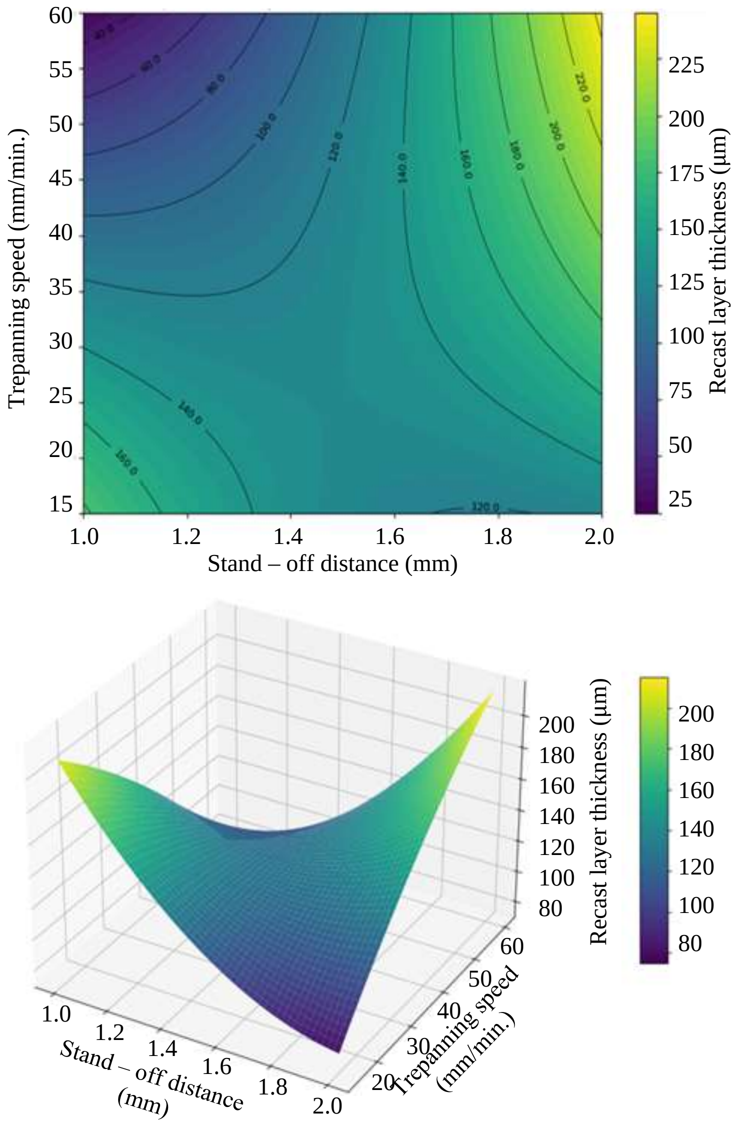


Figure 12. (a) and (b) Interactive effect of trepanning speed and stand-off distance.

CONCLUSIONS

(a) The recast layer is formed as a result of the fast heating and cooling that takes place during the laser drilling process, according to literature. The molten material re-solidifies on the hole walls after the laser passes, creating the recast layer. The laser warms the material, melting its surface.

(b) Major process variables including assist gas pressure, current, standoff distance, and trepan speed affect the recast layer's thickness and characteristics.

(c) Four process parameters were used in the experimental work, which was carried out in accordance with the Box-Behnken design (BBD): Trepan speed = 15–55 mm/min, Standoff distance = 1–1.8 mm, Current = 180–260 amp, and Assist gas pressure = 5–9 bar.

(d) Optimal range of process parameter are found from the 3D plots and contour plots
Assist gas pressure-7–8 bar
Current- 250–260 A
Stand-off distance- 1.5–1.6 mm
Trepanning speed- 40–55 mm/min.

Future Scope

Future research can focus on the systematic exploration and application of advanced machine learning techniques to the laser drilling process. These techniques can enable improved prediction of process parameters. An Integrated study can be done for applying machine learning tools with experimental and simulation-based studies. This could provide deeper insights into process–material interactions, ultimately contributing to enhanced efficiency, precision, and sustainability of laser drilling applications. Study conducted in this research can be extended for different types of fiber material as mentioned in [21–23, 25] and bio mass based materials [24].

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