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Experimental Investigation on Process Parameters of Nd: YAG Laser Drilling

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ABSTRACT

For some specific applications quality of the hole is much of the need and it is defined by its dimensional accuracy at entrance and exit of hole. Laser drilling is an advanced technology in drilling process, known for its accuracy, fastness and cleanliness in material removal to get the accurate hole diameters to the range of 5 microns. It gives the feasibility to drill the holes of very small aspect ratio. Nd: YAG Laser drilling process is an economical and easily regulated conventional drilling process compared to that of WEDM, punching, broaching and other prevalent destructive processes. This laser drilling technology is equipped with advanced features, provides ease of regulating the different input parameters. Some of the many input parameters that are involved in this operation are power, lamp current, pulse width, wavelength, pulse frequency etc., every input parameter has got its influence on output responses. With this consideration, experimentation is carried out selecting austenitic stainless steel known for its wide applications based on central composite design to examine the effect of laser input parameters particularly lamp current, pulse frequency, gas pressure and pulse width, on the quality of drilled holes. In total 31 experimental trials were conducted to get output responses. With response surface methodology (RSM) technique models were simulated for output responses and then compared with adequacy test. It is found that the response surface methodology predicted models are in close agreement with that of experimental values, further using evolutionary algorithms these models can be used for optimization of process parameters. Results are also useful to automate the laser drilling process.

Introduction

Laser drilling process is one of the advanced drilling techniques for producing high aspect ratio holes with a depth to diameter ratio much greater than 10:1. This laser drilled high aspect ratio holes are having applications in oil and gas machineries, engine blocks, cooling holes in aerospace turbine engine, laser fusion components and printed circuit board micro-vias [1]. Laser drilling process is also well suited for machining advanced hard and difficult to machine materials. This is one of the finest and widely used technique for producing holes, geometries and complex shapes in all engineering materials like metal, ceramics, composites, super alloys and non-metals also [2]. Manufacturers of turbine engines for aircraft propulsion and for power generation have benefited from the productivity of lasers for drilling small (0.3–1 mm diameter) typical cylindrical holes at 15–90° to the surface in cast, sheet metal and machined components. Their ability to drill holes at shallow angles to the surface at rates of between 0.3 to 3 holes per second has enabled new designs incorporating film-cooling holes for improved fuel efficiency, reduced noise, and lower NOx and CO emissions [3]. Incremental improvements in laser process and control technologies have led to substantial increases in the number of cooling holes used in turbine engines.

Fundamental to these improvements and increased use of laser drilled holes is an understanding of the relationship between process parameters and hole quality and drilling speed [4]. Pulsed Nd: YAG laser drilling technique is a popular machining process because of its high laser beam intensity, low means beam power, better focusing characteristics due to very small pulse duration and narrow heat affected zone. In this technique, in pulsed mode, high incident peak power output facilitates drilling of thick materials and it has advantage of enhanced transmission through plasma, wider choice of optical materials and flexibility in handling with the advent of fibre optic beam delivery [5]. For some special applications, the quality of drilled holes in pulsed Nd: YAG laser depends on many variable parameters such as pulse frequency, lamp current, pulse width, gas pressure and assist gap type etc. In this drilling process hole taper occurs due to converging-diverging shape of laser beam profile. Also regulating the hole diameters at both entry and exit is difficult job since laser drilling is based on the interaction of a laser beam with material undergoes a large number of parameters to regulate the process [6]. But, it is necessary to get predefined hole diameters without taper. Modelling of the process is essential to be able to regulate these main characteristics.

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Different researchers have experimentally investigated the laser drilling process in order to analyse the influence of different process parameters on quality of drilled hole. Austenitic stainless steel has wide range of industrial applications along all engineering materials. This material is used in oil and gas industries, aircrafts, automobiles, utensils and medical applications etc. [8]. Austenitic stainless steel is well suitable material to process by laser due to its characteristics. During laser drilling on austenitic stainless steel material laser power, pulse frequency, pulse width and gas pressure have their significant influence on entry and exit diameters of hole [9]. In the past years trial and error method is used for experimentation but by using this method material wastage and more time is consumed for process. To avoid these difficulties and by keeping in view the important constraints, a Central Composite Design (CCD) is used for experimentation and to analyse the parameters influences Response Surface Methodology (RSM) methodology is used [10]. Biswas et al. examined the influences of input variable parameters on circularity of hole at entrance and hole taper during Nd: YAG laser drilling on ceramic composite TiN-Al_2O_3 [11]. Bandhopadhayay et al. examined the influences of input variable parameters on diameter of hole and hole taper angle during Nd: YAG laser drilling on sheets of thick IN718 and Ti-6Al-4V [12]. Optimum parameters conditions are required to automate any process. To find the optimum parameter conditions of process, study of influences of process variable parameters is necessary. The objective of this research is to investigate experimentally the influences of process parameters during Nd: YAG laser drilling on austenitic stainless steel.

Experimental Setup and Details

The experiment is conducted by using robot assisted Nd:YAG laser drilling machine on austenitic stainless steel 304L material which is available at Meera Laser Solutions, Ambattur, Chennai, India. This laser system contains different subunits such as laser generating source, beam delivery unit, power supply unit, radio frequency (RF) Q- switch driver unit, cooling unit and robot controller for X, Y, Z, XY, YZ and ZX axis movements. Laser head consists of Nd: YAG rod and krypton circular segment beam which are put in two diverse nodes of convergence of a curved resin. Nd: YAG crystal is energized by krypton curve light. By using lens conveyance system, the laser is focused on work area. The prime power supply unit controls the laser yield by controlling force of the beam discharged by krypton curve beam. DC stepper motors are engaged to every pivot and are connected with the control unit. Figure 1 represents the robot assisted Nd: YAG laser drilling system. For visualization of drilling area and for clear centering state of work piece surface a CCD camera along with a CCTV screen is equipped in system. Assist gas supply unit is utilized during drilling.

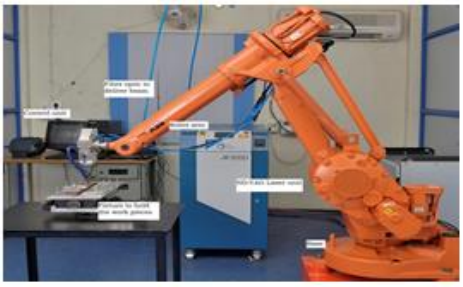

Fig 1. Robot assisted Nd: YAG laser drilling system.

The passage line of the packed gas goes through the dampness separator and it also contains a weight valve. This controlling valve is used to supply assist gas at different pressures to the laser drilling region.

Austenitic stainless steel 304L material is used in this work. By keeping in view of long literature survey, the selected input variable parameters are lamp current, pulse frequency, pulse width and gas pressure. The ranges and coded values of selected variable input parameters are tabulated in Table 1. By using CCD method the drilling runs are designed. As per run order and conditions drilling operation is conducted by laser drilling systems. After drilling the holes, diameters at entrance and exit are measured by tool maker's microscope setup and average value is calculated by Equation 1. Hole taper is calculated by using Eq. 2. The run order and run conditions as per coding along with measured output responses are tabulated in Table 2. RSM technology is used to analyse influences of parameters by using Design Expert 10 software.

Table 1. The coded and actual values of input variables.

Variables	Levels				
	-2	-1	0	1	2
Lamp current (A)	19	20	21	22	23
Pulse frequency (kHz)	0.4	0.8	1.2	1.6	2.0
Gas pressure (kg/cm^2)	0.5	1.0	1.5	2.0	2.5
Pulse width (%)	2	6	10	14	18

Table 2. Plan of process parameters for experiment, setting as per coding and measured responses.

Run order	Input parameters				Responses		
	Lamp current	Pulse frequency	Gas pressure	Pulse width	Diameter at entrance	Diameter at exit	Hole Taper (radians)
1	20	0.8	1.0	6	1.015	0.910	0.105
2	22	0.8	1.0	6	1.013	0.896	0.117
3	20	1.6	1.0	6	1.042	0.929	0.113
4	22	1.6	1.0	6	1.030	0.899	0.131
5	20	0.8	2.0	6	1.006	0.899	0.107
6	22	0.8	2.0	6	1.038	0.914	0.123
7	20	1.6	2.0	6	1.010	0.897	0.113
8	22	1.6	2.0	6	1.026	0.901	0.125
9	20	0.8	1.0	14	1.003	0.921	0.082
10	22	0.8	1.0	14	0.962	0.875	0.086
11	20	1.6	1.0	14	1.003	0.925	0.077
12	22	1.6	1.0	14	0.950	0.865	0.085
13	20	0.8	2.0	14	1.010	0.929	0.080
14	22	0.8	2.0	14	1.001	0.924	0.077
15	20	1.6	2.0	14	0.986	0.915	0.070
16	22	1.6	2.0	14	0.968	0.891	0.077
17	19	1.2	1.5	10	1.053	0.966	0.087
18	23	1.2	1.5	10	1.020	0.921	0.098
19	21	0.4	1.5	10	0.984	0.890	0.094
20	21	2.0	1.5	10	0.973	0.881	0.091
21	21	1.2	0.5	10	1.006	0.900	0.106
22	21	1.2	2.5	10	1.016	0.919	0.096
23	21	1.2	1.5	2	1.080	0.932	0.148
24	21	1.2	1.5	18	1.001	0.938	0.063
25	21	1.2	1.5	10	1.021	0.929	0.092
26	21	1.2	1.5	10	1.022	0.929	0.092
27	21	1.2	1.5	10	1.039	0.942	0.097
28	21	1.2	1.5	10	1.038	0.942	0.096
29	21	1.2	1.5	10	1.037	0.939	0.098
30	21	1.2	1.5	10	1.038	0.944	0.094
31	21	1.2	1.5	10	1.034	0.944	0.090

$$\text{Hole Diameter(mm)} = \frac{D_{min} + D_{max}}{2} \quad (1)$$

$$\text{Hole Taper (rad)} = \frac{(\text{hole entrance diamter}) - (\text{hole exit diameter})}{2 \times \text{thickness of the workpiece}} \quad (2)$$

Results and Discussions

By using output response values and input conditions which are tabulated in Table 2, empirical model equations eq. 3, 4, 5 are developed to predict the hole output responses.

$$y_{\text{diameter at entrance}} = 1.03 - 0.013x_1 - 0.004675x_2 + 0.003708x_3 - 0.038x_4 - 0.012x_1x_2 + 0.032x_1x_3 - 0.038x_1x_4 - 0.024x_2x_3 - 0.026x_2x_4 + 0.017x_3x_4 - 0.004593x_1^2 - 0.063x_2^2 - 0.030x_3^2 - 0.0008435x_4^2 \quad (3)$$

$$y_{\text{diameter at exit}} = 0.94 - 0.021x_1 - 0.005333x_2 + 0.007333x_3 + 0.00100x_4 - 0.015x_1x_2 + 0.035x_1x_3 - 0.027x_1x_4 - 0.019x_2x_3 - 0.015x_2x_4 + 0.024x_3x_4 - 0.003429x_1^2 - 0.061x_2^2 - 0.037x_3^2 - 0.012x_4^2 \quad (4)$$

$$y_{\text{hole taper}} = 0.94 + 0.00800x_1 + 0.0006667x_2 - 0.003667x_3 - 0.039x_4 + 0.0040x_1x_2 - 0.00250x_1x_3 - 0.011x_1x_4 - 0.00450x_2x_3 - 0.012x_2x_4 - 0.0070x_3x_4 - 0.001560x_1^2 - 0.001560x_2^2 + 0.006940x_3^2 + 0.011x_4^2 \quad (5)$$

Table 3. Square, R-Square and R-Square (adjusted) values of outputs.

Responses	Square-value	R-Square value	R-Square (adjusted) value
Diameter at entrance	0.001584	0.9452	0.8972
Diameter at exit	0.001074	0.9282	0.8654
Hole taper	0.003152	0.9856	0.9730

It is found from Table 3, that the values of R^2 and adjusted R^2 values for the output responses i.e., diameter of hole at entrance, at exit and hole taper are closer to each other. This means that the developed models can represent the process adequately.

Analysis of Effect of Input Parameters on Entrance Diameter

During the laser drilling process pulse frequency and lamp current have significant impact on output parameters. The interaction effect of pulse frequency and lamp current on hole diameter at entrance are shown in fig. 2. It was recognized that, when lamp current increases hole diameter is increased at all levels due to high lamp current exhibit high heat energy, due to which large amount of material is removed instantly from surface of workpiece. It is also observed that, when pulse frequency increases hole entrance diameter initially increases and decreases following a parabolic curve. This is because, initially when pulse frequency rises, pulse off time is shorter so pulse strikes quickly on surface of workpiece resulting in more amount of material removed and a large diameter is formed. Further increasing pulse frequency, pulse off time becomes very short ultimately resulting in less amount of material removed and small diameter is formed.

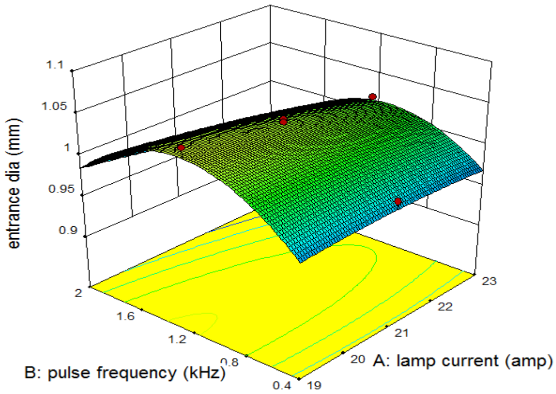

Fig 2. Interaction effect of pulse frequency and lamp current on entrance hole diameter.

Fig. 3 shows the interaction effect of pulse width and gas pressure on hole entrance diameter. At initial stage better hole diameter is obtained but while increasing pulse width, hole diameter is reduced by following a straight line. At low pulse width intensity of beam is high, resulting in good hole diameter but while increasing pulse width beam intensity is reduced, which results in small diameter at entrance.

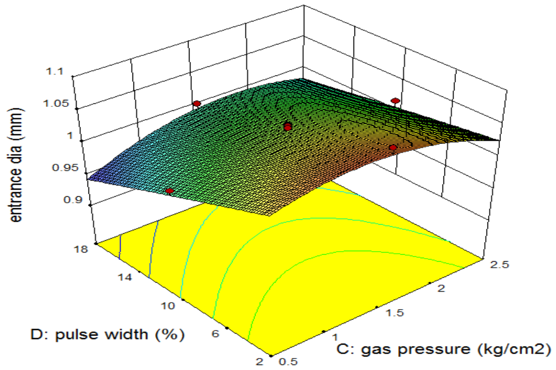

Fig 3. Interaction effect of pulse width and gas pressure on entrance hole diameter.

Analysis of Effect of Input Parameters on Exit Diameter

By constant assist gas pressure when pulse frequency is increased exit hole diameter increases and with further increase diameter gets reduced following a parabolic curve. This is because; by increasing pulse frequency successive intervals between alternative pulses are reduced which results in more material removal from top surface and also from bottom end

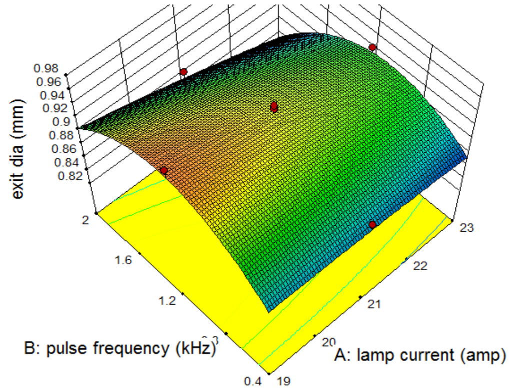

Fig. 4 Interaction effect of pulse frequency and lamp current on exit hole diameter

Fig. 4 shows interaction effects of pulse frequency and lamp current on hole diameter at exit. Hole diameter at exit increases with increase in lamp current by following a straight line. When lamp current increases intensity of beam as result more amount of material is removed. The interaction effects of pulse width and gas pressure on exit diameter is shown in Fig 5.

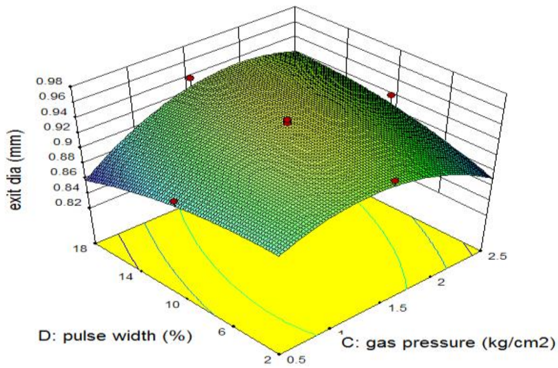

Fig 5. Interaction effect of pulse width and gas pressure on exit hole diameter.

Hole diameter at exit was reduced with increase in pulse width because while increasing pulse width intensity of beam gets reduced as a result small amount of material was removed from bottom. When gas pressure is increased exit diameter is also increased and with increasing gas pressure exit diameter is reduced following a nonlinear curve. Assist gas is used to ablate the material at drilling area. When gas pressure increased, a large amount of material is removed at faster rate as a result laser beam impinges upto bottom and diameter at bottom is increased. With further increase there was a little reduction but obtained diameter value is above that of the value at low gas pressure levels.

Analysis of Effect of Input Parameters on Hole Taper

Hole taper is dependent on entrance and exit diameters of hole. Fig. 6 shows the interaction effect of pulse frequency and lamp current on hole taper. Hole taper decreases with increase in pulse frequency and gets slightly increased at high levels of pulse frequency.

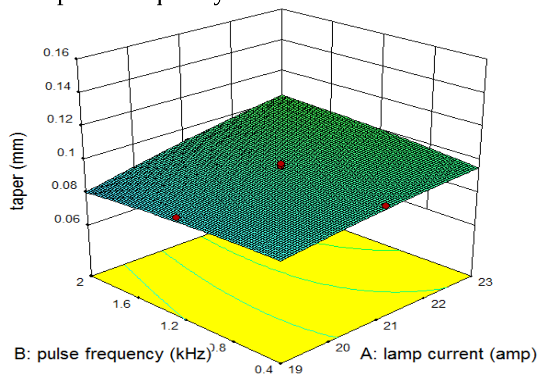

Fig 6. Interaction effect of pulse frequency and lamp current on hole taper.

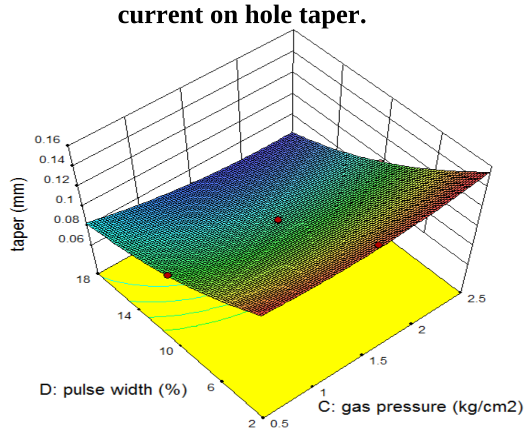

Fig 7. Interaction effect of pulse width and gas pressure on hole taper.

Interaction effect of pulse width and gas pressure on hole taper is shown in fig. 7. Hole taper was found to decrease with increasing pulse width and increase was noticed with increasing gas pressure. The reason for this is at lower levels of pulse width the difference between diameters of hole at entrance and exit is high but at higher levels of pulse width the diameters difference is low and vice versa with gas pressure.

Conclusion

In this paper, we investigated pulsed Nd: YAG laser drilling of austenitic stainless steel material. The interaction effects of process parameters (i.e., lamp current, pulse frequency, pulse width and gas pressure) on the drilled hole quality (entrance and exit diameters of hole and hole taper) were analyzed by conducting experiments based on CCD that led to the following conclusions: lamp current has a significant influence along all three input parameters. The optimum values of diameter at entrance has been considered at intermediate levels of lamp current, high levels of pulse frequency, intermediate levels of pulse width and gas pressure. Next the optimum values of diameter at exit has been considered at low levels of lamp current, high levels of pulse frequency, intermediate levels of pulse width, and lower levels of gas pressure. The Nd: YAG laser drilling system proved to be efficient in performing the drilling operations on austenitic stainless steel. It can be concluded that the input parameters can be optimally regulated for obtaining the good quality of hole in Nd: YAG laser drilling process.

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