Experimental Investigation of Quality Characteristics in Nd:YAG Laser Drilling of Stainless Steel (AISI 316)

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Abstract
Micro-machining of advanced engineering materials such as stainless steels, titanium alloys, nickel alloys, and ceramics is a challenging task due to properties like high strength to weight ratio, toughness, slenderness ratio, and low thermal conductivity. Stainless steel of grade AISI 316 has wide applications in medical science, automobile engineering, aviation, and aerospace industry due to their favourable material properties such as low thermal conductivity, high corrosion resistance, and high strength to weight ratio. Micro-machining of AISI 316 with high aspect ratio is a difficult task due to excessive heat generation, micro-structural changes, and tool breakage. Laser beam machining (LBM) process is a suitable alternative machining process, since it localizes the heat source to control the micro-structural changes. The difficulty arises during laser drilling because of spatter area and heat affected zone (HAZ), which adversely affects the quality of laser drilled holes. The present study attempts to experimentally investigate the effect of laser process parameters such as pulse width, laser energy, pulse frequency, and flushing pressure on the performance measures such as spatter deposition and heat affected zone (HAZ) during drilling operation. To reduce the total number of experimental run and obtain maximum information for the experimental trials, Taguchi L_{27} has been adopted. Analysis of variance (ANOVA) is performed to identify significant laser parameters influencing both the performance measures. From the study, it is revealed that pulse width is the most significant parameter in the formation of spatter and HAZ. From the results, it is identified that spatter area initially increases with increase in pulse frequency and then decreases for any level of pulse width. As pulse frequency increases, laser power increases resulting in more heat input into the material. This causes increase in vapour pressure inside the laser drilled hole, more material ejection, and increase in spatter area. However, laser supported absorption (LSA) waves developed at higher value of pulse frequency brings about blockage of laser energy from the material surface as an engrossing plasma, which results in reduction of material ejection and reduction in spatter area. It is observed that HAZ increases with increase in pulse width and pulse frequency. It may be due to higher average power of the laser beam, which is directly proportional to pulse width and pulse frequency. Higher the value of pulse width, higher will be the laser thermal energy and higher HAZ.

1. Introduction

Increase in the demand of machining of advanced engineering materials such as nickel alloys, titanium alloys, stainless steels is a challenging task. Availability of high power lasers have made it possible to machine such materials. In laser beam machining, a laser beam is focused on the material at required position and high heat flux is generated to remove material by melting and vaporization. Use of laser provides several advantages i.e., increase in the range of materials such as metals, alloys, composites, and plastics to machine, non-contact machining, machining of materials at micro scale range, minimize the finishing operation, minimize the heat affected zone (HAZ) due to localized heat generation. Nd:YAG lasers are effectively used for drilling metals and metal alloys.

Bandyopadhyay et al. [1] have performed Nd:YAG laser drilling of Inconel 718 and Ti6Al4V to understand the effect of process parameters such as pulse energy, pulse duration, pulse repetition rate, standoff distance of nozzle, type of gases, gas pressure, and focal position on the quality characteristics of laser drilled holes such as spatter deposition, taper, and recast layer. They have pointed out that focal position of the nozzle, pulse width, and laser energy are the significant parameters for laser drilling. Bandyopadhyay et al. [2] have performed laser percussion drilling of Inconel 718 and Ti6Al4V alloys of thickness 4 mm and 8 mm using Nd:YAG laser. Their study emphasizes study of the quality characteristics of the laser drilled holes in terms of geometrical features and metallurgical features. The geometrical features such as taper and hole diameter and metallurgical features such as heat affected zone, recast layer and taper. From the study it was noted that by fixing the laser parameters spatter and HAZ increases with increase in thickness. Their study also points out that machining of Inconel 718 and Ti6Al4V of same thickness and under identical laser machining condition HAZ and recast layer is thicker for Ti6Al4V. Yan et al. [3] have studied the effect of laser parameters, i.e., laser peak power, pulse duty cycle, pulse duration, and pulse repetition rate on quality characteristics such as taper and spatter. The laser drilling was performed on alumina using CO_2 laser by varying the control parameters. Numerical model was proposed to predict the taper during laser drilling process. Kaur et al. [4] have performed experimental investigation of laser drilling of zirconia using Nd:YAG laser. The analysis was performed to know the machining characteristics such as HAZ and taper formation and to obtain a condition to minimize the machining characteristics. It is observed that taper and HAZ increases with increase in lamp current. Low et al. [5] have performed laser drilling of Nimonic 263 using Nd:YAG laser. The study was performed to know the behavior of laser process parameters, i.e., laser energy and pulse width on the quality characteristics such as spatter deposition and ratio of diameter at entrance face to the diameter at the exit face ($d_{entrance}/d_{exit}$). The study was performed by keeping other parameters constant like pulse frequency, laser focal distance and gas pressure. The study suggests that spatter area increases and $d_{entrance}/d_{exit}$ decreases with increase in laser energy. Rajesh et al. [6] have adopted design of experimental approach to perform laser drilling of stainless steel using Nd:YAG laser. The study was performed to obtain mathematical model for performance measures, i.e., circularity at entry and exit and taper of laser drilled holes. From the study, a numerical model was proposed, which can be used for optimization of the control parameters such as lamp current, pulse frequency, pulse width, and gas pressure using evolutionary algorithm to predict the optimal parametric setting. Yilbas [7] have performed laser drilling of three different materials such as titanium, nickel, and stainless steel using Nd:YAG laser. The statistical analysis was performed to know the effect of process parameters on the hole quality and material properties. The quality of hole is considered in terms of re-solidified materials, taper, and barreling. The study states that with increase in thickness taper decreases and mean hole diameter increases with increase in laser pulse energy. Ghoreishi et al. [8] have performed laser drilling of stainless steel of grade 304 using Nd:YAG laser to understand the effect of laser process parameters such as laser peak power, laser pulse width, pulse frequency, number of pulses, assist gas pressure and focal plane position (f.p.p.) on performance measures such as hole taper, hole entrance diameter and hole circularity. The study was performed using design of experiment approach using response surface methodology to reduce the experimental trial. The study suggests that peak power and laser pulse width are the significant factors affecting drilled hole diameter. With increase in peak power or pulse width, hole entrance diameter increases. Lower hole taper is attained at high peak power, positive f.p.p., high number of pulses, and at high gas pressure.

Literature survey reveals that few attempts have been made on laser drilling of stainless steel using Nd:YAG laser. Studies were more focused on quality characteristics such as spatter, taper and hole diameter. After attaining aforementioned quality characteristics, it is also required to concentrate on major quality characteristics, i.e., heat affected zone (HAZ). The present study attempts to experimentally investigate the effect of laser process parameters such as pulse width, laser energy, pulse frequency, and flushing pressure on the performance measures such as spatter deposition and heat affected zone (HAZ) during drilling operation. To reduce the total number of experimental run and obtain maximum information for the experimental trials, Taguchi L_{27} has been adopted.

2. Experimental Procedure

In the present study, laser drilling of AISI 316 of thickness 0.5mm has been performed using pulsed Nd:YAG laser having wavelength of 1.06µm and laser beam radius of 200 µm. Argon has been used as an assist gas for flushing the molten materials and pressure range was kept between 4 to 8 bar. The laser process parameters selected for the experimentation are laser energy, pulse repetition rate, pulse width, and gas pressure. Each experimentation was repeated twice and an average value was noted for the performance measures such as heat affected zone and spatter area. In the present investigation, design of experiment (DOE) approach has been adopted using Taguchi L_{27} to understand the effect of process parameters on the performance measures. The experimental process parameters with their levels are as given in Table 1.

Table 1.Nd:YAG laser drilling control parameters and their levels

Sl. No.	Process parameters	Symbols	Unit	Levels		
				1	2	3
1	Laser Energy	A	J	10.182	18.835	30.185
2	Pulse Repetition Rate	B	Hz	1	4	7
3	Pulse Width	C	ms	4	6	8
4	Gas Pressure (Argon gas)	D	bar	4	6	8

3. Results and Discussion

In order to understand the effect of process parameters on the performance measures, this analysis has been performed. To measure the spatter area, the laser drilled material has been observed under optical microscope (Radial instrument with Samsung camera setup, 30X magnification). Using image processing toolbox in MATLAB 15a, spatter area has been measured (see Fig. 1). Laser machining is a thermal machining process, a huge amount of energy is conducted into the work piece leading to change in microstructure, material properties and phase composition such as changes in grain size and formation of oxide near the heat affected zone (HAZ). The laser drilled samples were observed under optical microscope to obtain images of the laser drilled holes and to measure the HAZ (Fig. 2). HAZ thickness was measured using the following equation 1.

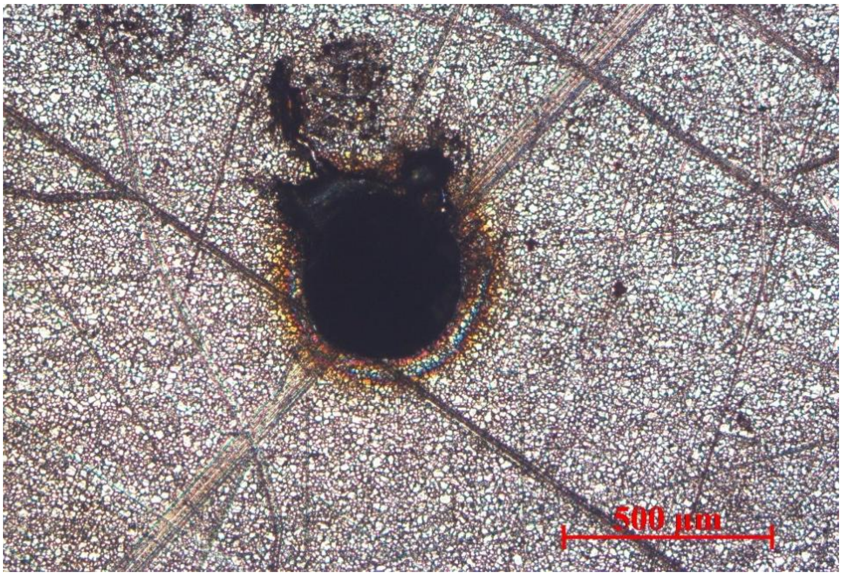

Fig. 1. Spatter deposition near laser drilled hole.

Fig. 2. Calculation of HAZ for laser drilling.

$$\text{Heat affected Zone, HAZ} = \frac{D_{outer} - D_{inner}}{2} \quad (1)$$

To know the significance of process parameters, statistical analysis using analysis of variance (ANOVA) has been performed for each performance measures. Coefficient of determination (R^2) for spatter area and HAZ are 98.4% and 94.6% respectively, showing the statistical significance of the analysis. Analysis of variance (ANOVA) for the performance measures such as HAZ and spatter area is shown in Table 2 and 3. It is observed that pulse width and pulse repetition rate are the most important factors contributing for spatter area and HAZ, respectively.

Table 2. ANOVA for spatter area

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**% Contribution**
A	2	37768436	37768436	18884218	9.43	5.6287
B	2	2.24E+08	2.24E+08	1.12E+08	55.84	33.3355
C	2	3E+08	3E+08	1.5E+08	74.92	44.7229
D	2	73121212	73121212	36560606	18.25	10.8973
Residual Error	18	36051346	36051346	2002853		
Total	26	6.71E+08				

Table 3. ANOVA for HAZ

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**% Contribution**
A	2	53659	53659	26829	112.66	20.3573
B	2	205261	205261	102630	430.95	77.8725
C	2	149	149	74	0.31	00.0565
D	2	230	230	115	0.48	00.0873
Residual Error	18	4287	4287	238		
Total	26	263586				

Main effect plot for performance measures such as spatter area and HAZ is shown in Fig. 3. Main effect plot helps to understand the effect of control parameters on performance measures. Spatter area and heat affected zone increases monotonously with increase in laser energy (Fig. 3). Laser power increases with increase in laser energy, this leads to generation of excessive heat inside the hole, which causes high material removal rate due to which spatter area increases. Higher laser energy leads to generation of high temperature and produces higher HAZ. Spatter area and heat affected zone increases with increase in pulse width (Fig. 3). It may be due to higher average power of the laser beam which is directly proportional to laser pulse width. Higher the value of pulse width, higher will be the laser thermal energy and higher HAZ. Similarly, the analysis has been performed for other performance measures.

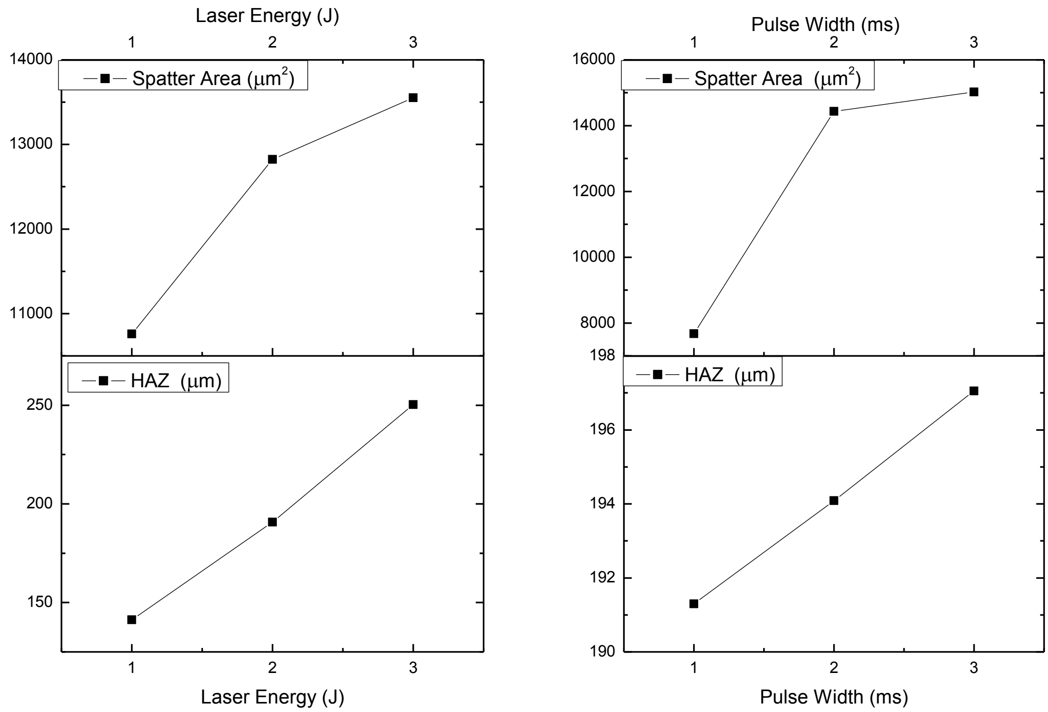

Figure 3. Spatter area and HAZ as a function of laser energy and pulse width.

4. Conclusion

Laser drilling of stainless steel (AISI 316) for thin plates (thickness of 0.5 mm) has been performed using pulsed Nd:YAG laser. The present investigation has been performed to determine the effect of laser process parameters such as laser energy, pulse repetition rate, pulse width and gas pressure on the performance measures, i.e. spatter area and heat affected zone (HAZ). Experimental and statistical analysis suggests that laser energy and pulse width are the most significant factors affecting spatter area. Similarly, laser energy and pulse repetition rate are significant factors affecting HAZ. The study also shows that spatter area and HAZ increases with increase in laser pulse energy and pulse width. The performance measures can be controlled by precise control of the laser process parameters. Minimum spatter area and HAZ can be attained at low level of laser energy and pulse width and at higher values of gas pressure.

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