Optimisation of hole characteristics in pulsed Nd: YAG laser micro-drilling of AISI 304 stainless steel by Taguchi method

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Abstract. The objective of this experimental study is to determine the influence of laser drilling parameters on a flat AISI 304 stainless steel sheet of 1mm thickness with pulsed Nd:YAG laser machining system. Taguchi's L25 orthogonal array is used for the experimental design. The machining process parameters such as Lamp current, Pulse frequency, Air pressure and Pulse width are optimized with heat affected zone and hole taper parameters. Grey Relational Analysis (GRA) is used to solve such correlated multi-attribute optimization of drilling operation. The optimal setting parameters for multiple performance characteristics is lamp current at level-1, pulse frequency at level-5, air pressure at level-4 and pulse width at level-5 i.e., l₁-f₅-p₄-w₅. The Analysis of Variance (ANOVA) technique is carried out to check the significance of the models and observed that the lamp current, pulse frequency and air pressure are significant at 95% confidence level. Finally in the confirmation test, it is observed that the grey relational grade is improved from initial process parameter combination.

1. Introduction

The laser micro-drilling process is one of the non-traditional machining process which uses thermal energy to remove material from the work piece surface and hence any complex geometries and difficult to machine materials can be machined easily without any tool-based problem [1, 2]. Due to highly directional, high power density and better focussing characteristics of laser beam; it is useful in processing of several materials. Due to the shorter wavelength (1 µm), and pulse mode, Nd: YAG laser can be absorbed by highly reflective materials which are difficult to machine by CO₂ lasers [3]. Experimental studies on Laser Drilling operations by various researchers show the effect of input process parameters such as laser power, lamp current, pulse frequency, pulse width, pulse number, spot diameter, focal plane position, type and pressure of assist gas, cutting material thickness and its composition, cutting speed, and mode of operation (continuous or pulsed mode) on process performance of interest in Laser drilling operation which are MRR (material removal rate), machined geometry (hole circularity, hole taper, hole diameter, aspect ratio, penetration depth), surface quality (surface morphology, Burr deposition rate, spatter), metallurgical characteristics (recast layer, heat affected zone), drilling efficiency and mechanical properties (crack, hardness, strength, etc.).

Due to converging or diverging shape of the laser beam, there always taper exists in laser drilled holes, which can be minimized up to acceptable range [4, 7, 9] by increasing the laser power at constant pulse frequency and the main change in metallurgical characteristics of laser machined parts
or work piece is mostly governed by HAZ and recast layer and it is seen that low material thickness and pulse energy gives smaller HAZ [5, 6, 10].

In this work, an experimental investigation has been performed on pulsed Nd: YAG laser micro-drilling of AISI 304 stainless steel. Four independent process parameters, lamp current, pulse frequency, air pressure, and pulse width are considered as input parameters. And the hole taper and HAZ width are considered as the output parameters. The Taguchi method [8] combined with the grey relational analysis [11] is used as a statistical design of the experiment technique to set the optimal process parameters. This optimal result is further verified with ANOVA.

2. Principle of Laser beam drilling

The mechanism of material removal during laser beam drilling consists of three different phases such as (i) melting, (ii) vaporization, and (iii) chemical degradation (chemical bonds are broken which causes the materials to degrade [12, 13]. Being a thermal process, the effectiveness of laser drilling depends on thermal properties and, to a certain extent, the optical properties rather than the mechanical properties of the material to be machined. Block diagram of laser micro drilling showing mechanical mechanism is shown in Figure 1.

![Figure 1. Block diagram of laser micro drilling showing mechanical mechanism](image)

3. Experimental procedure

The experiments were carried out on a flat AISI 304 stainless steel sheet of 1mm thick with composition (C %< 0.08, Si %< 1, Mn%<2, P%<0.045, S%<0.030, Cr% 18-20, Ni% 8-10.6). The work piece thickness was measured by a digital vernier calliper having a least count of 0.001 mm, and is found 1 mm. The work piece was held on the CNC work table using a specially designed fixture.

A 200W pulsed Nd: YAG laser-based CNC machining system, supplied by Suresh Indu-Laser, Pune (India) is used for the experimental study, with subsystems such as power supply unit, the laser source and beam delivery unit, cooling unit, radio frequency Q-switch driver unit, compressed air supply unit, and CNC controllers for X, Y, and Z axes movements. The photographic view of the CNC pulsed Nd: YAG laser machining system is shown in Figure 3.

Taguchi method for four factors at five levels was used for the implementation of orthogonal array experiments. An L25 orthogonal array with 25 rows and 4 columns was employed in this work. The experiments were carried out according to the arrangement of the orthogonal array. After the drilling operation, the top and bottom diameters of the micro-holes were measured by an optical measuring microscope (Model SDM-TR-MSU, Sipcon instrument Industries, India) at ×10 magnification. Taper of the drilled hole has been calculated considering the straight taper profile, and the HAZ width had been measured from the top surface only shown in Figure 2 as follows:
\[ Taper = \frac{(\text{hole \_dia}_{\text{top}} - \text{hole \_dia}_{\text{bottom}})}{2 \times \text{thickness}} \]  
(1)

\[ HAZ \text{ width} = \frac{(\text{HAZ \_dia}_{\text{top}} - \text{hole \_dia}_{\text{top}})}{2} \]  
(2)

The experimental layout for the laser drilling parameters using the L_{25} orthogonal array and the experimental results and their S/N ratio values are presented in Table 1.

![Figure 2. HAZ width of drilled hole from top surface](image1)

![Figure 3. CNC pulsed Nd: YAG laser M/C system](image2)

| Expt. no | Lamp current (lamp) (actual) | Pulse frequency f (kHz) (actual) | Air pressure p(kg/cm²) (actual) | Pulse width w(%) (actual) | HAZ S/N ratio | TAPER S/N ratio |
|----------|-----------------------------|---------------------------------|-------------------------------|-------------------------|---------------|----------------|
| 01       | 16                          | 0.3                             | 0.5                           | 03                      | 0.2608        | 11.6738        | 0.0653         | 23.7017       |
| 02       | 16                          | 1.3                             | 1.0                           | 08                      | 0.1709        | 15.3452        | 0.0612         | 24.2650       |
| 03       | 16                          | 2.3                             | 1.5                           | 13                      | 0.2298        | 12.7730        | 0.0613         | 24.2508       |
| 04       | 16                          | 3.3                             | 2.0                           | 18                      | 0.2041        | 13.8031        | 0.0618         | 24.1802       |
| 05       | 16                          | 4.3                             | 2.5                           | 23                      | 0.0936        | 20.5745        | 0.0598         | 24.4660       |
| 06       | 18                          | 0.3                             | 1.0                           | 13                      | 0.3902        | 8.1743         | 0.0598         | 24.4660       |
| 07       | 18                          | 1.3                             | 1.5                           | 18                      | 0.3702        | 8.6313         | 0.0531         | 29.6034       |
| 08       | 18                          | 2.3                             | 2.0                           | 23                      | 0.2560        | 11.8352        | 0.0549         | 26.0729       |
| 09       | 18                          | 3.3                             | 2.5                           | 03                      | 0.2782        | 11.1292        | 0.0601         | 24.4225       |
| 10       | 18                          | 4.3                             | 0.5                           | 08                      | 0.2315        | 12.7090        | 0.0678         | 23.3754       |
| 11       | 20                          | 0.3                             | 1.5                           | 23                      | 0.3408        | 9.3500         | 0.0529         | 25.5309       |
| 12       | 20                          | 1.3                             | 2.0                           | 03                      | 0.3319        | 9.5799         | 0.0424         | 27.4527       |
| 13       | 20                          | 2.3                             | 2.5                           | 08                      | 0.2989        | 10.4895        | 0.0542         | 25.3200       |
| 14       | 20                          | 3.3                             | 0.5                           | 13                      | 0.3302        | 9.6245         | 0.0798         | 21.9599       |
| 15       | 20                          | 4.3                             | 1.0                           | 18                      | 0.2618        | 11.6406        | 0.0783         | 22.1248       |
| 16       | 22                          | 0.3                             | 2.0                           | 08                      | 0.4912        | 6.1748         | 0.0761         | 22.3723       |
| 17       | 22                          | 1.3                             | 2.5                           | 13                      | 0.4986        | 6.0450         | 0.0785         | 22.1026       |
| 18       | 22                          | 2.3                             | 0.5                           | 18                      | 0.6724        | 3.4474         | 0.1052         | 19.5597       |
| 19       | 22                          | 3.3                             | 1.0                           | 23                      | 0.5986        | 7.9893         | 0.1189         | 18.4964       |
| 20       | 22                          | 4.3                             | 1.5                           | 03                      | 0.4014        | 7.9285         | 0.1068         | 19.4296       |
| 21       | 24                          | 0.3                             | 2.5                           | 18                      | 0.4803        | 6.3697         | 0.0812         | 21.8089       |
| 22       | 24                          | 1.3                             | 0.5                           | 23                      | 0.4269        | 7.3935         | 0.0689         | 23.2356       |
| 23       | 24                          | 2.3                             | 1.0                           | 03                      | 0.4907        | 6.0432         | 0.0916         | 20.7621       |
| 24       | 24                          | 3.3                             | 1.5                           | 08                      | 0.3412        | 9.3398         | 0.1021         | 19.8195       |
| 25       | 24                          | 4.3                             | 2.0                           | 13                      | 0.3221        | 9.8402         | 0.0773         | 22.2364       |

4. Optimization of individual performance characteristics

4.1 Determination of optimal process parameters for HAZ and Taper

In this section, L_{25} orthogonal array is used to determine the optimal process parameters. Machining results are reported in using S/N ratio and ANOVA analysis by using statistical software MINITAB-14. In Taguchi there are three performance characteristics such as higher-is-better, nominal-is-better
and lower-is-better. Here lower-is-better is used to find the optimal process parameter for HAZ and Taper.

4.2 Analysis of $S/N$ ratio for HAZ

As the experimental design is orthogonal, so it is possible to separate out the effect of each process parameter at different levels. From the response Table 2 of mean $S/N$ ratio for HAZ, it is observed that current is the most effective parameter followed by frequency and pulse width. It is also observed that air pressure has least effect on HAZ.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
Symbol & Process parameters & Level-1 & Level-2 & Level-3 & Level-4 & Level-5 & Max-Min & Rank \\
\hline
l & Current & 14.834 & 10.493 & 10.137 & 6.317 & 7.797 & 8.517 & 1 \\
f & Frequency & 8.349 & 9.399 & 8.918 & 10.374 & 12.539 & 4.190 & 2 \\
p & Pressure & 8.970 & 9.838 & 9.605 & 10.247 & 10.918 & 1.949 & 4 \\
w & Width & 9.268 & 10.812 & 9.291 & 8.778 & 11.428 & 2.650 & 3 \\
\hline
\end{tabular}
\caption{Response table of mean $S/N$ ratio for HAZ}
\end{table}

From main effects plot for SN ratio (Figure 4), the optimal process parameters for HAZ are obtained such as lamp current at level-1, pulse frequency at level-5, air pressure at level-5 and pulse width at level-5 i.e., $l_1-f_5-p_5-w_5$.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{main_effects.png}
\caption{Main Effects Plot for SN ratios}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{mean_snr.png}
\caption{Mean S/N graph for HAZ}
\end{figure}

4.3. ANOVA for HAZ

The purpose of the ANOVA is to find the statistical significance of process parameters on the response shown in Table 3 and it is observed that the lamp current, pulse frequency and pulse width are with a P value less than 0.05 that means these are significant at 95% confidence level.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Source & DF & SS & MS & F & P \\
\hline
l & 4 & 0.262720 & 0.065680 & 54.77 & 0.000 \\
f & 4 & 0.063355 & 0.015839 & 13.21 & 0.001 \\
p & 4 & 0.012019 & 0.003005 & 2.51 & 0.125 \\
w & 4 & 0.030746 & 0.007687 & 6.41 & 0.013 \\
Error & 8 & 0.009593 & 0.001199 & & \\
Total & 24 & 0.378434 & & & \\
\hline
R-Sq = 97.47\% & R-Sq (adj) = 92.40\%
\end{tabular}
\caption{ANOVA table for HAZ}
\end{table}
4.4. Analysis of S/N ratio for Taper

Similarly the S/N ratio for Taper is calculated. Here lower-is-better is used to find the optimal process parameter for Taper. From response Table 4, it is observed that the current is again the most effective parameter for Hole taper followed by pulse frequency and air pressure. From the mean S/N ratio for Taper, the optimal process parameters are obtained such as lamp current at level-2, pulse frequency at level-2, air pressure at level-4 and pulse width at level-5 i.e., $I_2-f_2-p_4-w_5$. And the result is shown in Figure 5.

Table 4 Response table of mean S/N ratio for Taper

| Symbol | Process parameters | Level-1 | Level-2 | Level-3 | Level-4 | Level-5 | Max-Min | Rank |
|--------|-------------------|---------|---------|---------|---------|---------|---------|------|
| l      | Current           | 24.17   | 25.59   | 24.48   | 20.39   | 21.57   | 5.20    | 1    |
| f      | Frequency         | 23.58   | 25.33   | 23.19   | 21.78   | 22.33   | 3.56    | 2    |
| p      | Pressure          | 22.37   | 22.02   | 23.73   | 24.46   | 23.62   | 2.44    | 3    |
| w      | Width             | 23.15   | 23.03   | 23.00   | 23.46   | 23.56   | 0.56    | 4    |

Total mean S/N ratio = 23.24 dB

Figure 5. Mean S/N graph for Taper

4.5. ANOVA for Taper

From ANOVA analysis shown in Table 5, it is clearly found that lamp current, pulse frequency and air pressure with a P value less than 0.05 that means these are significant at 95% confidence level.

Table 5 ANOVA table for Taper

| Source | DF  | SS            | MS            | F   | P   |
|--------|-----|---------------|---------------|-----|-----|
| l      | 4   | 0.0065586     | 0.0016396     | 40.20 | 0.000 |
| f      | 4   | 0.0022398     | 0.0005600     | 13.73 | 0.001 |
| p      | 4   | 0.0013360     | 0.0003340     | 8.19  | 0.006 |
| w      | 4   | 0.0000281     | 0.0000070     | 0.17  | 0.947 |
| Error  | 8   | 0.0003263     | 0.0000408     |      |      |
| Total  | 24  | 0.0104889     |               |      |      |

R-Sq = 96.89%   R-Sq (adj) = 90.67%
5. Grey relation analysis

In the grey relational analysis, the experimental results are first normalized in the range between zero and unity. This process of normalization is known as the grey relational generation. After then the grey relational coefficient is calculated from the normalized experimental data to express the relationship between the desired and actual experimental data. Then, the overall grey relational grade is calculated by averaging the grey relational coefficient corresponding to each selected process response. The overall evaluation of the multiple process responses are based on the grey relational grade. This method converts a multiple response process optimization problem with the objective function of overall grey relational grade. The corresponding level of parametric combination with highest grey relational grade is considered as the optimum process parameter.

5.1 Determination of optimal process parameters for Grey relational grade

The higher grey relational grade implies that the corresponding parameter combination is closer to the optimal. Thus the grey relational grade with S/N ratio is found out which is shown in Table 6.

The optimal process parameters are obtained from the response graph as shown in Figure 6. The optimal setting parameters for multiple performance characteristics is lamp current at level-1, pulse frequency at level-5, air pressure at level-4 and pulse width at level-5 i.e., \( I_f - f_p - w_p \).

Table 6 Grey relational grade table

| Expt. No | Responses | Grey relational generation | Evaluation of \( \Delta_{mi} \) | Grey relational coefficient(\( \psi = 0.5 \)) | Grey relational grade | S/N ratio |
|----------|-----------|-----------------------------|-------------------------------|---------------------------------------------|-----------------------|---------|
|          | HAZ       | Taper                       | HAZ                           | Taper                                       | HAZ                   | Taper   |
| 01       | 0.2608    | 0.0653                      | 0.820738                      | 0.624709                                    | 0.197262              | 0.375291 |
| 02       | 0.1709    | 0.0612                      | 1                             | 0.672494                                    | 0                      | 0.327506 |
| 03       | 0.2298    | 0.0613                      | 0.882552                      | 0.671329                                    | 0.117448              | 0.328671 |
| 04       | 0.2041    | 0.0618                      | 0.933799                      | 0.665501                                    | 0.066201              | 0.334499 |
| 05       | 0.0936    | 0.0598                      | 1.154138                      | 0.688811                                    | -0.15414             | 0.311189 |
| 06       | 0.3902    | 0.0598                      | 0.562712                      | 0.688811                                    | 0.437288              | 0.311189 |
| 07       | 0.3702    | 0.0331                      | 0.602592                      | 1                                            | 0.397408              | 0.557161 |
| 08       | 0.256     | 0.0497                      | 0.830309                      | 0.806527                                    | 0.169691              | 0.193473 |
| 09       | 0.2782    | 0.0601                      | 0.786042                      | 0.685315                                    | 0.213958              | 0.314685 |
| 10       | 0.2315    | 0.0678                      | 0.879163                      | 0.595571                                    | 0.120837              | 0.404429 |
| 11       | 0.3408    | 0.0529                      | 0.661216                      | 0.769231                                    | 0.338784              | 0.230769 |
| 12       | 0.3319    | 0.0424                      | 0.678963                      | 0.891608                                    | 0.321037              | 0.108392 |
| 13       | 0.2989    | 0.0542                      | 0.744764                      | 0.754079                                    | 0.255234              | 0.425921 |
| 14       | 0.3302    | 0.0798                      | 0.682353                      | 0.457511                                    | 0.317647              | 0.542829 |
| 15       | 0.2618    | 0.0783                      | 0.818744                      | 0.473193                                    | 0.182156              | 0.526087 |
| 16       | 0.4912    | 0.0761                      | 0.361316                      | 0.498834                                    | 0.638684              | 0.501166 |
| 17       | 0.4986    | 0.0785                      | 0.34656                       | 0.470862                                    | 0.65344               | 0.529138 |
| 18       | 0.6724    | 0.1052                      | 0.159674                      | 1                                            | 0.840326              | 0.333333 |
| 19       | 0.3986    | 0.1189                      | 0.545962                      | 0                                            | 0.454038              | 0.333333 |
| 20       | 0.4014    | 0.1068                      | 0.540379                      | 0.140126                                    | 0.459621              | 0.858974 |
| 21       | 0.4803    | 0.0812                      | 0.383051                      | 0.439394                                    | 0.616949              | 0.560606 |
| 22       | 0.4269    | 0.0689                      | 0.489531                      | 0.582751                                    | 0.510469              | 0.417249 |
| 23       | 0.4987    | 0.0916                      | 0.346361                      | 0.318182                                    | 0.653639              | 0.681818 |
| 24       | 0.3412    | 0.1021                      | 0.660419                      | 0.195804                                    | 0.339581              | 0.804196 |
| 25       | 0.3221    | 0.0773                      | 0.698504                      | 0.484848                                    | 0.301496              | 0.515152 |

5.2. ANOVA for Grey relational grade

From the Table 7, it is clearly found that lamp current, pulse frequency and air pressure with a P value less than 0.05 that means these are significant at 95% confidence level.
5.3. **Confirmation test for Grey relational grade**

After the optimum level of machining parameters in multiple performance characteristics identified, a verification test needs to be carried out in order to check the accuracy of the analysis. Table 8 shows the comparison of estimated grey relational grade with the actual grey relational grade obtained in experiment using the optimal drilling parameters.

**Table 8 Results for the confirmation tests**

| Initial process parameter | Optimal process parameter | Prediction | experiment |
|---------------------------|---------------------------|------------|------------|
| Level                     | I-f-p-w                     | I-f-p-w     | 1-f-p-w     |
| HAZ                       | 0.5412                      | 0.1686     | 0.5587     |
| Taper                     | 0.1021                      | 0.083368   | 0.832505   |
| Grey relational Grade     | 0.48946                     | -0.0833638 | 0.35       |

It is also found that the improvement of grey relational grade from initial process parameter combination to the optimal process parameter combination is 0.35.

6. **Conclusions**

The laser micro-drilling operation on AISI 304 stainless steel was performed using pulsed Nd: YAG laser machining system. The optimal process parameters (lamp current, pulse frequency, air pressure and pulse width) combination on both HAZ and Hole Taper has been determined by a multi response optimization technique. The use of the Taguchi orthogonal array with grey relational analysis to
optimize the machining process with the multiple performance characteristics is used in this work. The grey relational grade, which is a grey relational analysis of the experimental results of HAZ and taper, is used for conversion of single performance characteristics optimization and the improvement of grey relational grade from initial process parameter combination to the optimal process parameter combination is 0.35. As a result, optimization of the complicated multiple performance characteristics was simplified through this approach. It is shown that the performance characteristic of the machining process such as HAZ and Taper are improved together by using this approach.

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