Experimental investigation of Hole geometry on Laser Drilling of AA8090-T3 Al-Li Alloy using Taguchi Method

Haja Syeddu Masooth P[1], Nagarajan P[2]
[1] Lincoln University College, Malaysia; [2] Lincoln University College, Malaysia;
pdf.masooth@lincoln.edu.my

Abstract
Laser drilling is a promising non-contact technique for creating precision holes in lightweight aluminum-lithium alloys utilised in cutting-edge engineering applications. The geometric characteristics of laser-drilled holes in AA8090-T3 aluminum-lithium alloy under various parameters of laser power, scanning speed, and pulse frequency are analysed experimentally in this study. A Taguchi L_{27} experimental design was employed, resulting in 27 experimentally drilled holes. The geometric quality of the holes was evaluated using a coordinate measuring machine (CMM) in terms of hole diameter, diameter deviation, roundness, cylindricity and perpendicularity. The measured hole diameter varied from 3.0455 to 3.1937 mm against a nominal diameter of 3.000 mm, while roundness, cylindricity and perpendicularity deviations ranged from 0.0218–0.1952 mm, 0.0520–0.1789 mm and 0.0089–0.1732 mm**,** respectively. The experimental results reveal considerable variation in hole geometry with changes in the laser processing conditions. The minimum values of the individual geometric deviations were obtained at different parameter combinations, demonstrating the response-dependent nature of laser drilling.

Keywords: AA8090-T3; aluminium-lithium alloy; laser drilling; geometric accuracy; CMM; roundness; cylindricity; perpendicularity.

1. Introduction

Aluminium-lithium alloys are important lightweight materials for aerospace and advanced engineering applications because lithium additions can reduce density while increasing specific stiffness. AA8090 is an aluminium-lithium alloy developed for high strength-to-weight applications. Despite these benefits, creating precise holes in AA8090 is still difficult since the final hole shape is highly dependent on how the laser beam interacts with the workpiece. A non-contact machining technique that can create tiny holes without traditional tool-workpiece interaction is laser drilling. Because femtosecond laser processing's ultrashort pulse duration restricts the amount of time available for heat diffusion and permits highly localised material removal, it is especially appealing for precision machining. However, the chosen laser parameters and drilling circumstances continue to affect the final dimensional accuracy. The energy provided to the workpiece is influenced by laser power, scanning speed, and pulse frequency, which in turn affects hole geometry. Predictive modelling and rigorous experimental design are therefore helpful in determining parameter combinations linked to increased geometric accuracy. Artificial neural networks may depict nonlinear relationships between process inputs and outputs, whereas Taguchi methods offer an effective experimental framework.

Thus, the current study uses a Taguchi L27 experimental design and CMM-based geometric characterisation to examine femtosecond laser drilling of AA8090-T3. ANN-based prediction and statistical analysis are performed using the measured responses. Establishing a data-driven approach to enhance the dimensional quality of laser-drilled holes is the main goal.

2. Methodology

The initial material chosen and produced for the workpiece was AA8090-T3. Then, utilising three chosen process parameters, femtosecond laser drilling was carried out. A Taguchi L27

orthogonal array was used to plan the experiments, yielding 27 experimental holes. A CMM was used to measure the holes' geometric properties. The obtained dataset was then utilised for ANN modelling and virtual prediction after being examined using Taguchi techniques. The aluminum-lithium alloy AA8090-T3 was chosen as the material for the workpiece. An AA8090 sheet with a thickness of 3 mm was used for the experiment. For traceability, the material was purchased with material certification. To ensure solid alignment during laser processing, the workpiece surface was cleaned and firmly fastened prior to drilling. The AA8090-T3 workpiece was drilled using a femto-second laser system. The process parameters identified for the experimental study were laser power, scanning speed, and pulse frequency. The Process parameters were periodically varied: scanning speed, power of the laser, and frequency of pulses. The experimental set of values used in the 27-hole dataset is presented in Table 1. A Taguchi L_{27} orthogonal array was used to cover all combinations of three factors at three levels.

Table 1. Selected laser drilling process parameters.

Factor	Level 1	Level 2	Level 3
Scanning speed (mm/s)	75	82.5	90
Laser power (W)	60	70	80
Pulse frequency (Hz)	4500	5000	5500

The AA8090-T3 plate was fixed on the drilling platform and aligned with the laser system. For each trial, the required scanning speed, laser power, and pulse frequency were selected according to the L_{27} experimental matrix. A total of 27 holes were produced. The experimental conditions were maintained as consistently as possible throughout the trials, and the resulting holes were subsequently subjected to dimensional inspection. A coordinate measuring machine was used to characterize the geometry of all 27 drilled holes. Measurements were obtained at multiple depths of the hole, including the entry, midsection, and exit regions. Multiple circumferential points were collected to determine the geometric characteristics of the drilled holes. The CMM dataset provided the basis for evaluating diameter, roundness, cylindricity and perpendicularity.

3. Taguchi Analysis

The Taguchi method was used to analyze the influence of the three laser parameters on hole geometry. Since the geometric error responses are minimized, the smaller-the-better S/N characteristic is appropriate. The S/N ratio was calculated as:

$$S/N = -10 \log_{10}[(1/n)\, \Sigma(y_i^2)]$$

where y_i is the measured response and n is the number of observations. Main-effect plots were then used to compare the response means at the three levels of each process parameter. The resulting trends were used to identify parameter levels associated with lower geometric deviation.

4. Results and Discussion

Table 2 represents the experimental results of Hole diameter (mm), Roundness deviation (mm), Cylindricity (mm) and Perpendicularity (mm).

4.1 Experimental Hole-Diameter Results

The measured hole diameters for the 27 experimental conditions ranged from 3.0455 to 3.1937 mm. The nominal target diameter was 3.000 mm. The smallest recorded diameter was found for Hole 4 at 75 mm/s, 70 W, and 4500 Hz, whereas the largest recorded diameter was for Hole 14 at 82.5 mm/s, 70 W, and 5000 Hz. The observed variation proves

that the set values of laser parameters affect the drilled hole sizes. Figure 1 depicts the changes in hole diameter obtained from the 27 experimental tests. The observations of hole diameter ranges from 3.0455 to 3.1937 mm, in contrast to the nominal diameter of 3.000 mm. The experimental run 4 shows the smallest diameter of 3.0455 mm, whereas the run 14 reveals the largest diameter of 3.1937 mm. The differences of diameter suggest that variation in laser power, scanning speed, and pulse frequency affect the volume of material displaced around the shape characteristics. All the measurements exceeding the nominal value indicate that the experimental conditions explored in this study typically resulted in an enlargement of hole size. The noted variability indicates the necessity for precise regulation of femto-second laser processing ranges when dimensional precision is essential.

Table 2. Experimental results

S. No.	Cutting Speed [mm/s]	Laser Power [W]	Laser Frequency [Hz]	Hole diameter [mm]	Roundness [mm]	Cylindricity [mm]	Perpendicularity [mm]
1	75	60	4500	3.1608	0.0886	0.1185	0.0174
2	75	60	5000	3.1459	0.0645	0.138	0.0333
3	75	60	5500	3.1432	0.0326	0.1374	0.0267
4	75	70	4500	3.0455	0.0578	0.1023	0.0596
5	75	70	5000	3.152	0.0375	0.1064	0.0538
6	75	70	5500	3.0619	0.1314	0.1536	0.1188
7	75	80	4500	3.1682	0.0889	0.0985	0.0302
8	75	80	5000	3.1856	0.0218	0.1111	0.0217
9	75	80	5500	3.1254	0.0457	0.1092	0.0181
10	82.5	60	4500	3.1063	0.0852	0.1425	0.1299
11	82.5	60	5000	3.1297	0.1183	0.112	0.0468
12	82.5	60	5500	3.1218	0.0525	0.0685	0.048
13	82.5	70	4500	3.1107	0.1952	0.1789	0.1732
14	82.5	70	5000	3.1937	0.0446	0.1025	0.0706
15	82.5	70	5500	3.1449	0.0451	0.1038	0.0581
16	82.5	80	4500	3.0951	0.0977	0.0848	0.0183
17	82.5	80	5000	3.1282	0.0606	0.1398	0.0675
18	82.5	80	5500	3.0675	0.1189	0.052	0.0228
19	90	60	4500	3.1582	0.0776	0.1657	0.0741
20	90	60	5000	3.1293	0.097	0.1035	0.0089
21	90	60	5500	3.114	0.0689	0.1061	0.0769
22	90	70	4500	3.095	0.1073	0.0673	0.0543

23	90	70	5000	3.1378	0.0902	0.1143	0.0602
24	90	70	5500	3.0912	0.0778	0.1198	0.0472
25	90	80	4500	3.145	0.1061	0.1171	0.0276
26	90	80	5000	3.0626	0.1376	0.1261	0.0721
27	90	80	5500	3.1155	0.0624	0.0861	0.0495

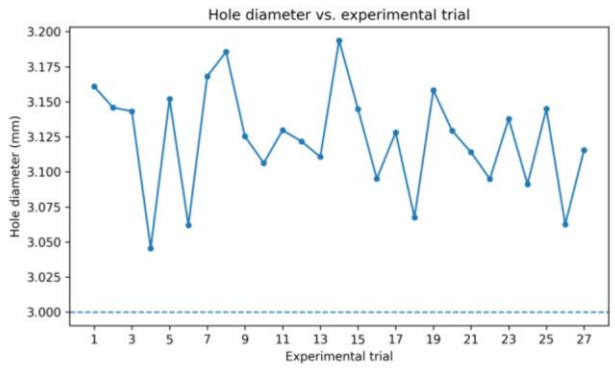


Fig. 1 Hole diameter deviation vs Experimental trial

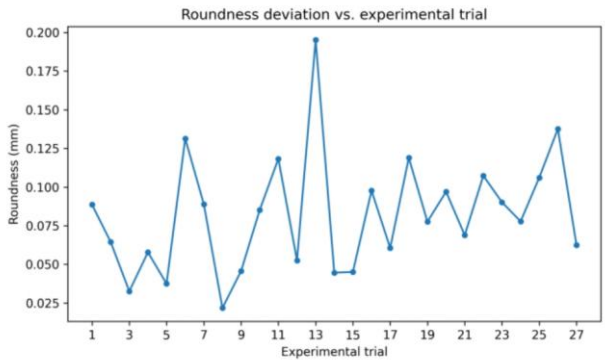


Fig. 2 Roundness deviation vs Experimental trial

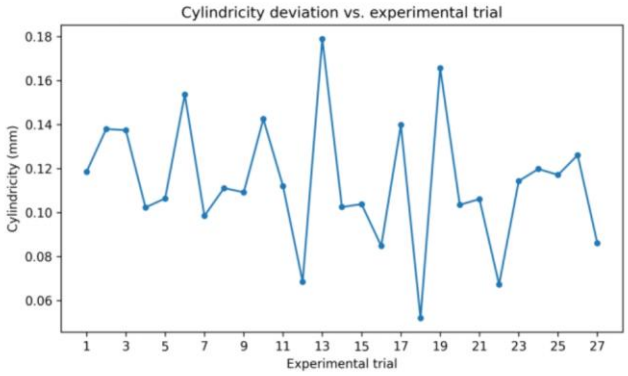


Fig. 3 Cylindricity deviation vs Experimental trial

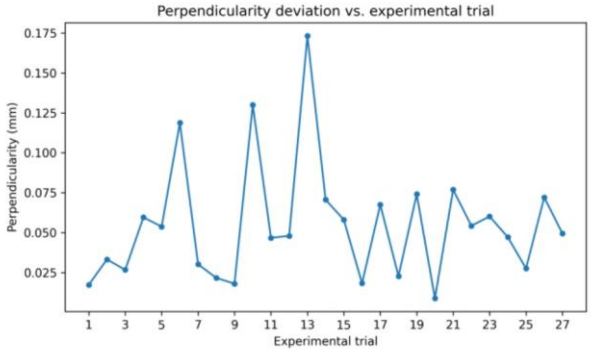


Fig. 4 Perpendicularity deviation vs Experimental trial

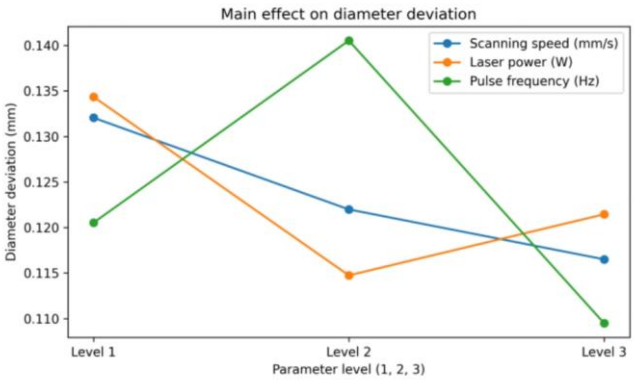


Fig. 5 Main effect on diameter deviation

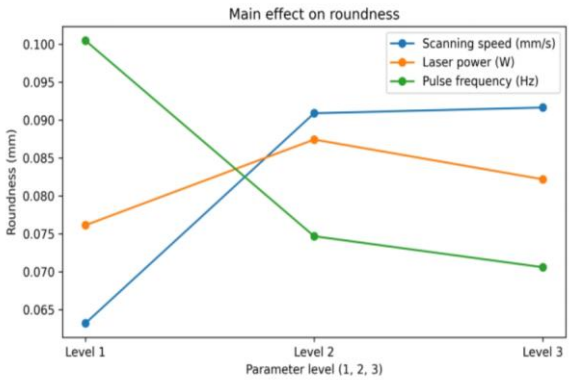


Fig. 6 Main effect on roundness

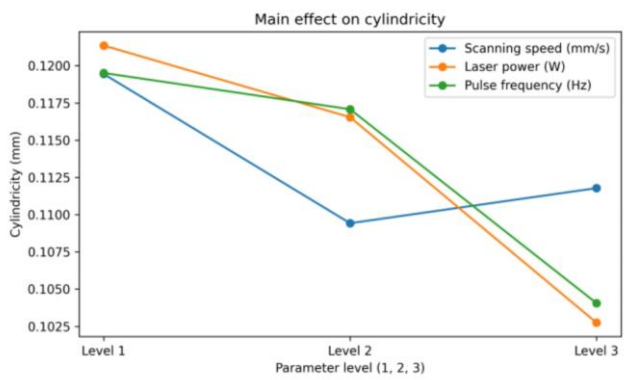


Fig. 7 Main effect on Cylindricity

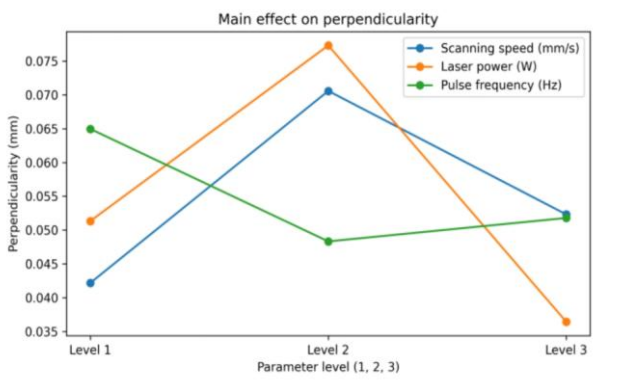


Fig. 8 Main effect on perpendicularity

4.2 Roundness Results

Figure 2 presents the roundness deviation obtained for the 27 experimental conditions. The measured roundness values range from 0.0218 to 0.1952 mm. The lowest roundness deviation is obtained in Trial 8**,** whereas the highest value is observed in Trial 13**.** The considerable variation between the experimental conditions indicates that the circularity of the drilled holes is sensitive to the selected laser-processing conditions. A lower roundness deviation indicates that the hole profile is closer to an ideal circular geometry. The results also show that achieving a smaller hole-diameter deviation does not necessarily result in the lowest roundness deviation, indicating that dimensional size and circular form are distinct aspects of hole quality.

4.3 Cylindricity Results

Figure 3 shows the variation in cylindricity deviation for the 27 drilled holes. The cylindricity values range from 0.0520 to 0.1789 mm**.** The minimum deviation is obtained in Trial 18**,** while the maximum value occurs in Trial 13**.** The variation indicates that the three-dimensional form of the drilled holes changes with the laser-processing conditions. Unlike hole diameter, which primarily represents dimensional size, cylindricity describes the consistency of the hole geometry along its depth. Therefore, the results demonstrate that satisfactory hole quality requires control of the hole form throughout its depth rather than relying only on the measured diameter.

4.4 Perpendicularity Results

Figure 4 illustrates the perpendicularity deviation measured for the 27 experimental trials. The measured values range from 0.0089 to 0.1732 mm. The minimum perpendicularity deviation is recorded in Trial 20**,** whereas the maximum value is observed in Trial 13**.** The relatively large difference between these values demonstrates that the selected processing conditions can influence the orientation of the drilled-hole axis relative to the reference surface. A smaller perpendicularity deviation indicates a better alignment of the hole axis with the desired direction. Consequently, perpendicularity offers an extra geometric-quality standard in addition to diameter and shape precision.

4.5 Main effect of process parameters on hole diameter

The fig. 5 depicts the main-effect plot for hole diameter, indicates that the average measured hole diameter significantly changes with scanning speed, laser power, and pulse frequency. Provided that the nominal hole diameter is 3.000 mm and all experimentally measured holes exceeded this value, the characteristics observed proves that the chosen laser parameters reliably created an larger hole. The differences in average hole diameter

across the parameter levels indicate that variation in the energy supplied to the workpiece affects the degree of material removal outside the desired hole perimeter. The response does not show a consistent monotonic trend across all three parameters, evidents that hole dimensional accuracy depends on the interaction of multiple processing conditions instead of just one parameter alone.

4.6 Main effect of process parameters on roundness

The fig. 6 for roundness illustrates significant differences in the average roundness deviation as scanning speed, laser power, and pulse frequency change. The variation in the response across the parameter levels indicate that the circularity of the drilled holes is influenced by the selected laser processing conditions. The response trend also shows that improvement in dimensional size does not necessarily result in a corresponding improvement in roundness. This observation is consistent with the experimental results, where the minimum roundness deviation was obtained at Trial 8 (0.0218 mm)**,** whereas the maximum deviation occurred at Trial 13 (0.1952 mm)**.** Thus, the main-effect plot highlights that hole circularity is a distinct geometric characteristic that needs to be evaluated independently during femto-second laser drilling.

4.7 Main effect of process parameters on cylindricity

The main-effect plot depicted in fig. 7 for cylindricity shows that the average cylindricity deviation varies across the different levels of scanning speed, laser power, and pulse frequency. These variations indicate that the processing conditions influence the three-dimensional form of the hole along its depth. Unlike hole diameter, which represents the dimensional size of the hole, cylindricity reflects deviations of the hole surface from an ideal cylindrical form. The experimental results further support this observation, with cylindricity values ranging from 0.0520 to 0.1789 mm. The minimum cylindricity deviation was obtained in Trial 18 (0.0520 mm)**,** while the maximum was observed in Trial 13 (0.1789 mm)**.** Therefore, the main-effect plot confirms that achieving accurate hole dimensions alone does not guarantee good cylindrical form.

4.8 Main effect of process parameters on perpendicularity

The main-effect plot depicted in fig. 8 for perpendicularity indicates that the average perpendicularity deviation changes with the levels of scanning speed, laser power, and pulse frequency. The variation demonstrates that the orientation of the drilled hole relative to the reference surface is affected by the selected laser processing conditions. The perpendicularity values varies between 0.0089 and 0.1732 mm. The least deviation obtained in Trial 20 is 0.0089 mm, while the highest value in Trial 13 is 0.1732 mm. The changes in the parameter-level averages confirms that the geometric precision of the hole is not defined by its diameter or roundness. Thus, perpendicularity variable suggest an additional examination of the positional and geometric quality of the holes drilled by femto-second lasers.

5. Conclusions

The femtosecond laser drilling of AA8090-T3 was analysed by laser power, scanning speed, and pulse frequency as the main process characteristics.

- An L_{27} orthogonal array based on Taguchi method was utilized to carry out 27 experimental tests, and the hole geometry were evaluated through Coordinate Measuring Machine.
- The analysis examined four main geometric characteristics: hole size, roundness, cylindricity, and perpendicularity.

- The experimental findings proved that quantifiable differences across all four responses with modifications in the laser processing parameters. The diameter range varied between 3.0455 and 3.1937 mm.
- The Taguchi method offers a structured approach to examine the impacts of laser process parameters. Future research should empirically confirm the parameter conditions derived from the ANN through more trials and an expanded dataset.

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