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Mathematical Modelling of the Nd:YAG Laser Microdrilling of Aluminium 5052 for Process Optimization and Analysis of Sensitivity

S. Mahanty, N. Roy[2,*], A. Kuar[2] and S. Mitra[2]

[1]*Indian Institute of Management Indore, Indore-453556, Madhya Pradesh, India*
[2]*Department of Production Engineering, Jadavpur University, Kolkata-700032, West Bengal, India*

Laser beam micromachining of aluminium 5052 was conducted to investigate the effect of four process parameters: lamp current; pulse frequency; pulse width; and assist gas pressure on quality characteristics of drilled hole. Hole taper and hole circularity are important attributes that effect the drilled hole quality are selected as machining responses. Response surface methodology (RSM) was used to design the experiments and to develop the mathematical model. A sensitivity analysis has been conducted on the developed mathematical model to determine the relative influence of different parameters on the process outputs.

Keywords: Nd:YAG laser, aluminium 5052 alloy, microdrilling, hole taper, hole circularity, mathematical model, response surface methodology (RSM), sensitivity analysis

1 INTRODUCTION

Al-alloys are widely used in engineering structures and components where light weight or corrosion resistance is required. The alloy aluminium 5052 is known for exceptional performance in extreme environments. It is highly resistant to corrosion attack in seawater, industrial chemical environments or in any hostile environment. It also retains exceptional strength after welding. It also has very good cold formability. It is a medium to high strength alloy

*Corresponding author: Tel: +91 9836725305; E-mail: nilanjan_83@yahoo.co.in

with strength and a medium to high fatigue strength. Aluminium 5052 alloys are commonly used in aircraft, other aerospace structures, amphibious vehicles like boat building and shipbuilding, and other marine and salt-water sensitive shore applications. Aluminium is increasingly used in microsystems technology such as electrodes in biotechnology applications [1].

Recent advances in the design, specifications and reliability of laser systems which have been designed as micro manufacturing alternatives to the aforementioned processes, has led to highly market driven research in implementing lasers in the micro manufacture of devices. Pulsed Nd:YAG laser radiation is a powerful tool for micromachining different materials because the laser radiation can be focused to micron-sized spot diameters and the thermal load can be controlled by changing the pulse length. To reduce material damage and thermal load, and to increase accuracy during micromachining by laser radiation, short pulse lengths, especially nano and picosecond laser pulses are employed [2].

Laser percussion drilling is extensively used in the industry for small hole fabrication, such as effusion cooling holes in aerospace components. Instead of mechanical properties, thermal and optical properties of the workpiece material control the efficiency of laser beam drilling for which laser drilling has rapidly become an inexpensive and controllable alternative to conventional hole drilling methods in the technologically advanced industries. While laser machining is a non-contacting and abrasionless technique eliminating tool wear, machine-tool deflections, vibrations and cutting forces, it also reduces limitations to shape formation with minimal sub- surface damage [3]. It is a drilling process whereby the work piece is subjected to a series of laser pulses at the same spot at a specialized setting, which results in melt ejection and consequently forming a hole. Efficiency of laser beam drilling process depends on the process parameters as well as the thermophysical properties of the workpiece.

Geometrical inaccuracies in terms of hole taper, circularity, recast layer formation, barrelling and spatter formation occur. The influence of the temporal pulse train shaping, effect of different assist gases on melt ejection is investigated by Low *et al.* [4]. Yilbas *et al.* [5] reported the effects of single pulse laser drilling parameters on the hole geometry and hole quality including recast, taper, barrelling, inlet cone, exit cone, surface debris and mean hole diameter. Hamoudi and Rasheed [6] investigated the effect of workpiece material properties, such as thermal diffusivity, on laser drilled hole geometry.

Some research has been done to control the quality of drilled hole *via* the development of statistical analysis. Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system (numerical or otherwise) can be apportioned to different sources of uncertainty in its inputs [7]. A related practice is uncertainty analysis, which has a greater focus on uncertainty quantification and propagation of uncertainty. Ideally, uncertainty and sensitivity analysis should be run in tandem. Sensitivity analysis can be useful for a range of purposes [8]. Including testing the robustness of the results of a model or system in the presence of uncertainty, increased understanding of the relationships between input and output variables in a system or model, searching for errors in the model (by encountering unexpected relationships between inputs and outputs). It also enables model simplification by fixing model inputs that have no effect on the output, or identifying and removing redundant parts of the model structure [9]. Very few studies have been performed on sensitivity analysis, especially for different manufacturing processes. Kim *et al.* [10] conducted a sensitivity analysis to compare relative impact of process parameters on bead geometry of gas metal arc (GMA) and concluded that with respect to process parameters related to penetration, the width and height of the bead are more sensitive to change. Gurjan and Murugan [11] conducted sensitivity anaylsis after optimizing the parameters to see the effect on the output for deviation in the optimal values of the parameters. Karaoglu and Secgin [12] performed the sensitivity analysis of weld bead parameters penetration to variations in current, voltage, and speed in submerged arc welding process. To-date no such study has been recorded on the laser micromachining of such usefull aluminum alloys.

This paper presents an experimental approach for determination of optimum laser machining parameters to get desired machining responses during pulsed Nd:YAG laser micro drilling of aluminium 5052 alloy. Lamp current, pulse frequency, pulse width and assist gas pressure have been chosen as independently controllable process variables. Hole taper and hole circularity are considered as process responses. Response surface methodology (RSM) was adopted to perform the experimental design and also to develop the mathematical relationships between the input process parameters and responses. A sensitivity analysis has been conducted on the developed mathematical model to determine the relative influence of different parameters on the process outputs.

2 PROPOSED METHODOLOGY

2.1 Experimental design based on response surface methodology (RSM)

Experiments have been carried out according to the central composite rotatable second-order design based on RSM. Response surface modelling was used to establish the mathematical relationship between the response, and the various machining parameters, with the eventual objective of determining the optimum operating conditions for the system. A general second-order polynomial response surface mathematical model was used to analyse the parametric influences on the various response criteria [13]:

$$\eta = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum_{i<} \sum_{j=2}^{k} \beta_{ij} x_i x_j \tag{1}$$

where η is the corresponding response, x represents the values of different machining parameters for different experiments, k is the number of experiments and β represents the second order regression coefficients.

2.2 Sensitivity analysis

Sensitivity analysis is the first and the most important step in the optimization problems, because it yields the information about the increment or decrement tendency of the design objective function with respect to the design parameter. Therefore, sensitivity analysis plays an important role in determining which parameter of the process should be modified for effective improvement. Mathematically, sensitivity of a design objective function with respect to a design variable is the partial derivative of that function with respect to its variables.

3 EXPERIMENTAL DETAILS

3.1 Material specifications

Aluminium 5052 sheets of thickness 0.78 mm are used as the workpiece material. Chemical composition, and the physical and mechnaical properties of the aluminium 5052 are given in Table 1 and Table 2, respectively.

3.2 Laser microdrilling arrangement and procedure

A pulsed Nd:YAG laser computer numerical control (CNC) machining system (M/s Sahajanand Laser Technology, Ltd.) was used for the experimental study. The detailed specification of the arrangement is given in Table 3. Figure 1 shows the pictorial view of pulsed Nd:YAG laser machining system. Lamp current, pulse frequency, assist gas pressure and pulse width are

TABLE 1
Physical and mechanical properties of the aluminium alloy 5052 used in this work.

Property	**Value**
Density	2.68 kg/m^3
Tensile strength	210 MPa
Elongation	14%
Modulus of elasticity	70 GPa
Melting point	605°C

TABLE 2
Specification details of the Nd:YAG laser used in this work.

Specification	**Description**
Laser type	Nd:YAG laser
Wave length	1064 nm
Mode of operation	Q-switched (pulsed)
Type of q-switch	Accousto-optic Q-switch
Mode of laser beam	Fundamental mode (TEM00)
Mirror reflectivity	Rear mirror100%, Front mirror 80%
Beam diameter 1/e2	1 mm
Laser beam spot diameter	100 μm
Average power	75 W
Pulse width	120 to 150 ns

TABLE 3
Chemical composition of the aluminium 5052 used in this work.

Element	**Precentage**
Mn	0.0-0.10
Fe	0.0-0.40
Cu	0.0-0.10
Mg	2.2-2.8
Si	0.0-0.25
Zn	0.0-0.10
Cr	0.15-0.25
Others	0.0-0.15
Al	Balance

considered as the controllable process parameters whereas hole taper and hole circularity are considered as machining responses to carry out the experiment. The ranges of these process parameters are selected on the basis of trial experiments conducted by using one factor at a time approach. Through holes were drilled in all experiments and each experiment was repeated two times.

3.3 Hole analysis techniques

A total of 32 sets of experiments have been carried out according to the central composite rotatable second-order design based on RSM. The levels of parameters selected are shown in Table 4.

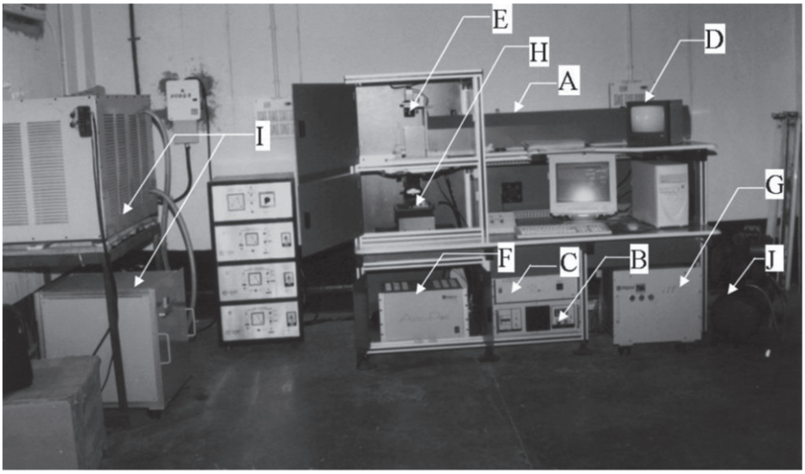

FIGURE 1
Photographic view of the Nd:YAG laser. A is the laser head, B is power supply unit, C is the RF Q-switch driver unit and CNC *x-y-z* work table, D is the CCTV, E is the CCD camera, F is the RF Q-switch driver unit, G is the chiller unit, H is the CNC controller unit, I is the heat exchanger unit and J is the air compressor.

TABLE 4
Level of the process parameters.

Parameters	Symbol	Levels				
		−2	−1	0	1	2
Lamp current (A)	x_1	21	22	23	24	25
Pulse frequency (kHz)	x_2	0.2	0.6	1.0	1.2	1.8
Pulse width (%)	x_3	1	2	3	4	5
Air pressure (kg/cm^2)	x_4	0.5	1.0	1.5	2.0	2.5

Average values of these repeated experiments (three times) are taken for further analysis. A general second-order polynomial response surface model has been developed to establish the mathematical relationship between the machining responses, and process parameters. The experimental results have been listed in Table 4. The thickness of the job sample was measured at different sections by a digital micrometre having a least count of 1 μm. After completion of the experiments, microscopic views of the microdrilled holes for both top and bottom surfaces were taken at 10× magnification with the help of an optical measuring microscope (STM6; Olympus, Ltd.). Hole taper is measured for each experimental result by analysing the microscopic view of perimeters of drilled holes at entry and exit using an image analysis software according to

$$\text{Taper(rad)} = \frac{\text{Hole\_dia}_{\text{Top}} - \text{Hole\_dia}_{\text{Bot}}}{2 \times \text{Thickness}} \tag{2}$$

The hole circularity at top and bottom surface has been measured by using the ratio of minimum to maximum Feret's diameters of the hole. All the machining responses are measured three times each for all the experimental runs and average of this is accounted for further analysis. Experimental observations are listed in Table 5. Statistical software MINITAB 17 is used here to establish second order polynomial models which are further used for sensitivity analysis.

4 SECOND ORDER POLYNOMIAL MODELLING OF THE RESPONSES

The effect of the process parameters on the responses have been correlated by using a RSM-based empirical model, established as follows.

$$\begin{aligned} \textit{Circularity} = {} & 6.034 - 0.4241X_1 + 0.4533X_2 - 0.2898X_3 \\ & -0.1014X_4 + 0.008894X_1^2 - 0.07340X_2^2 + 0.001444X_3^2 \\ & +0.00558X_4^4 - 0.02248X_1X_2 + 0.012067X_1X_3 + 0.00136X_1X_4 \\ & + 0.01798X_2X_3 + 0.07504X_2X_4 - 0.00806X_3X_4 \end{aligned} \tag{3}$$

and

$$\begin{aligned} \textit{Taper} = {} & -0.9841 + 0.09198X_1 + 0.0167X_2 + 0.02913X_3 \\ & -0.0284X_4 - 0.002055X_1^2 - 0.00362X_2^2 - 0.000730X_3^2 \\ & -0.000290X_4^2 - 0.000207X_1X_2 - 0.001368X_1X_3 + 0.000537X_1X_4 \\ & -0.000689X_2X_3 - 0.00133X_2X_4 + 0.004500X_3X_4 \end{aligned} \tag{4}$$

where X_1, $X_{2,}$ X_3 and X_4 indicate coded values of the process parameters lamp current, pulse frequency, pulse width and assist air pressure, respectively.

The analysis of variance (ANOVA) analysis table of the quadratic model for hole circularity is given in Table 6. Adequacy of the model is measured by the values of R^2, adjusted R^2 and predicted R^2 which are in the reasonable

TABLE 5
Experimental results.

Lamp Current (A)	Pulse Frequency (Hz)	Pulse Width (%)	Assist Air Pressure (bar)	Hole Taper (rad)	Hole Circularity
22	0.6	2	1.0	0.03699	0.89700
24	0.6	2	1.0	0.02614	0.89270
22	1.4	2	1.0	0.03868	0.86400
24	1.4	2	1.0	0.02724	0.82673
22	0.6	4	1.0	0.03452	0.87500
24	0.6	4	1.0	0.01922	0.91400
22	1.4	4	1.0	0.03430	0.85450
24	1.4	4	1.0	0.01934	0.87250
22	0.6	2	2.0	0.02680	0.87550
24	0.6	2	2.0	0.01842	0.86750
22	1.4	2	2.0	0.02699	0.87700
24	1.4	2	2.0	0.01820	0.85090
22	0.6	4	2.0	0.03418	0.82789
24	0.6	4	2.0	0.01897	0.87600
22	1.4	4	2.0	0.03374	0.86291
24	1.4	4	2.0	0.01787	0.87520
21	1.0	3	1.5	0.03324	0.89300
25	1.0	3	1.5	0.01084	0.90850
23	0.2	3	1.5	0.02682	0.85600
23	1.8	3	1.5	0.02905	0.82150
23	1.0	1	1.5	0.02937	0.86950
23	1.0	5	1.5	0.02529	0.87240
23	1.0	3	0.5	0.03398	0.88000
23	1.0	3	2.5	0.02596	0.86150
23	1.0	3	1.5	0.03004	0.86500
23	1.0	3	1.5	0.03072	0.86200
23	1.0	3	1.5	0.03007	0.86770
23	1.0	3	1.5	0.03147	0.87050
23	1.0	3	1.5	0.03059	0.86100
23	1.0	3	1.5	0.02929	0.86350
23	1.0	3	1.5	0.03034	0.86200

TABLE 6
ANOVA analysis of hole circularity.

Source	DF	Adj. SS	Adj. MS	F-Value	P-Value
Model	14	0.012490	0.000892	91.38	0.000
Linear	4	0.002685	0.000671	68.74	0.000
X_1	1	0.000220	0.000220	22.57	0.000
X_2	1	0.001852	0.001852	189.73	0.000
X_3	1	0.000006	0.000006	0.66	0.047
X_4	1	0.000605	0.000605	62.00	
Square		0.003989	0.000997	102.14	0.000
2-Way Interaction	6	0.005817	0.000969	99.30	0.000
Error	16	0.000156	0.000010		
Lack-of-Fit	10	0.000084	0.000008	0.70	0.707
Pure Error	6	0.000072	0.000012		
Total	30	0.012647			
S 0.0031247		R-sq 98.76%	R-sq(adj.) 97.68%	R-sq(pred.) 95.40%	

agreement and close to 1. P-value for the model as well as for all the process parameters in single term is less than 0.05 indicates that the model along with the all the process parameters are statistically significant at 95.0% confidence level. The lack-of-fit value of 0.707 implies that it is not significant which is desired.

The ANOVA analysis table of the quadratic model for hole circularity is given in Table 6. Adequacy of the model is measured by the values of R^2, adjusted R^2 and predicted R^2 which are in the reasonable agreement and close to 1. The P-value for the model as well as for all the process parameters in single term is less than 0.05 indicates that the model along with the all the process parameters are statistically significant at 95% confidence level The lack-of-fit value of 0.178 implies that it is not significant which is desired. Microscopic view of laser drilled hole is given in Figure 2 and Figure 3.

5 SENSITIVITY ANALYSIS OF MACHINING RESPONSES

To obtain the sensitivity equation of circularity (C) with respect to lamp current Equation (3) is partially differentiated with respect to lamp current. Now we have the sensitivity equation of circularity with respect to lamp current:

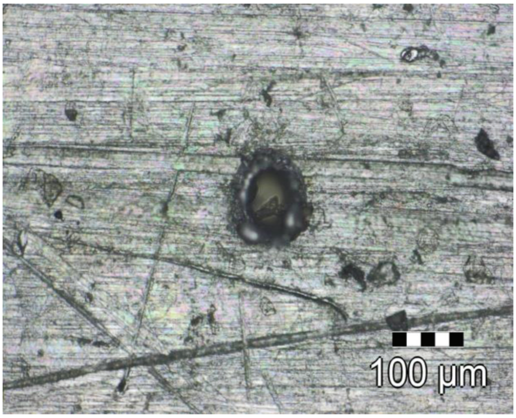

FIGURE 2
Optical micrograph of a Nd:YAG laser microdrilled microhole at the top surface.

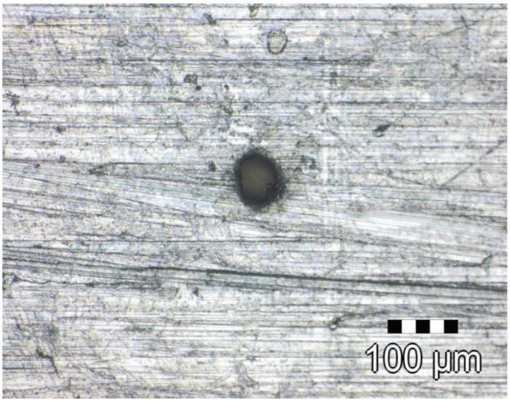

FIGURE 3
Optical micrograph of a Nd:YAG laser microdrilled microhole at the bottom surface.

$$\begin{aligned} \mathrm{d}C / \mathrm{d}X_1 = &-0.4241 + 0.017788X_1 - 0.02248X_2 \\ &+0.012067X_3 + 0.00136X_4 \end{aligned} \tag{5}$$

and the sensitivity equation of circularity with respect to pulse frequency:

$$\begin{aligned} \mathrm{d}C / \mathrm{d}X_2 = &\ 0.4533 - 0.1468X_2 - 0.02248X_1 \\ &+0.01798X_3 + 0.07504X_4 \end{aligned} \tag{6}$$

and the sensitivity equation of circularity with respect to pulse width:

$$\begin{aligned} dC/dX_3 &= -0.2898 + 0.002888X_3 + 0.012067X_1 \\ &+0.01798X_2 - 0.00806X_4 \end{aligned} \tag{7}$$

and the sensitivity equation of circularity with respect to assist air pressure:

$$\begin{aligned} dC/dX_4 &= -0.1014 + 0.01116X_4 + 0.00136X_1 \\ &+0.07504X_2 - 0.00806X_3 \end{aligned} \tag{8}$$

To obtain the sensitivity equation of hole taper (T) with respect to lamp current Equation (4) is partially differentiated with respect to lamp current. Now we have the sensitivity equation of hole taper with respect to lamp current

$$\begin{aligned} dT/dX_1 &= 0.09198 - 0.00411X_1 - 0.000207X_2 \\ &-0.001368X_3 + 0.000537X_4 \end{aligned} \tag{9}$$

and the sensitivity equation of hole taper with respect to pulse frequency:

$$\begin{aligned} dT/dX_2 &= 0.0167 - 0.00724X_2 - 0.000207X_1 \\ &-0.000689X_3 - 0.00133X_4 \end{aligned} \tag{10}$$

the sensitivity equation of hole taper with respect to pulse width:

$$\begin{aligned} dT/dX_3 &= 0.02913 - 0.00146X_3 - 0.001368X_1 \\ &-0.000689X_2 + 0.004500\mathrm{X}_4 \end{aligned} \tag{11}$$

and the sensitivity equation of hole taper with respect to assist air pressure:

$$\begin{aligned} dT/dX_4 &= -0.0284 - 0.00058X_4 + 0.000537X_1 \\ &-0.00133X_2 + 0.004500X_3 \end{aligned} \tag{12}$$

Sensitivity analysis is carried out to examine the influence of an input variable to the outputs within the design space considered in this research work. Positive values of sensitivities means that the output variable increases as the input variable increases and a negative value means that the output variable increases as the input variable decreases [12].

It is evident from Figure 4 that the sensitivity of lamp current on hole taper is negative. It indicates that with the increase in lamp current, hole taper decreases. Higher lamp current generates high thermal energy, which produces large taper. The low energy of laser beam generates small taper. High energy laser beam at higher lamp current with a small incident time may removes more material from the top surface almost instantly, rather than throughout the depth which increases the tapering effect. Also, from Figure 4 we infer that sensitivity of hole circularity gradually changes from negative to positive. This implies that the circularity increases with lamp current. This is due to the reason that when lamp current increases, the energy of laser beam also increases which in turn increases the material removal from the top surface of the work piece, due to which circularity improves.

From Figure 5 it is evident that sensitivity of pulse frequency on hole taper is positive for lower values of pulse frequency and negative for higher value of pulse frequency. The negative value of pulse frequency sensitivity of hole taper indicates a decrease in the value of hole taper with increase of pulse frequency. At high pulse frequencies, small taper is observed but at low pulse frequencies, large taper is generated. At a low pulse frequency, comparatively high beam energy is generated, which remove more material from top surface results in the high tapered hole. Again at lower pulse frequency, less energy beam generates small taper of microhole. From Figure 5 we can see that sen-

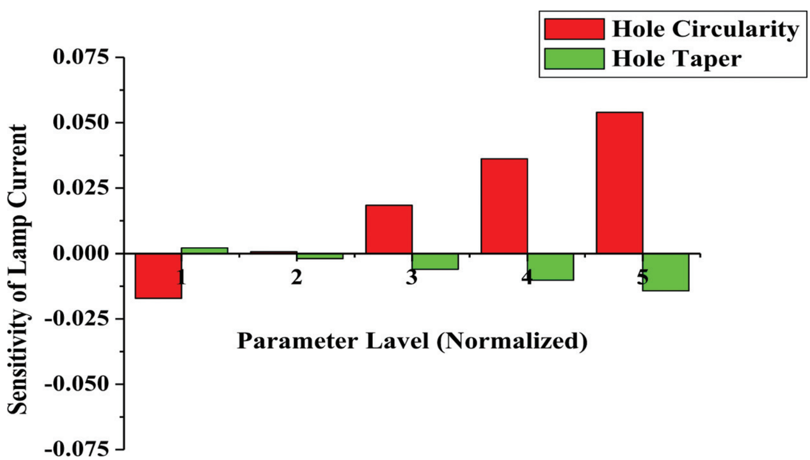

FIGURE 4
Bar chart showing sensitivity of lamp current in respect of machining responses.

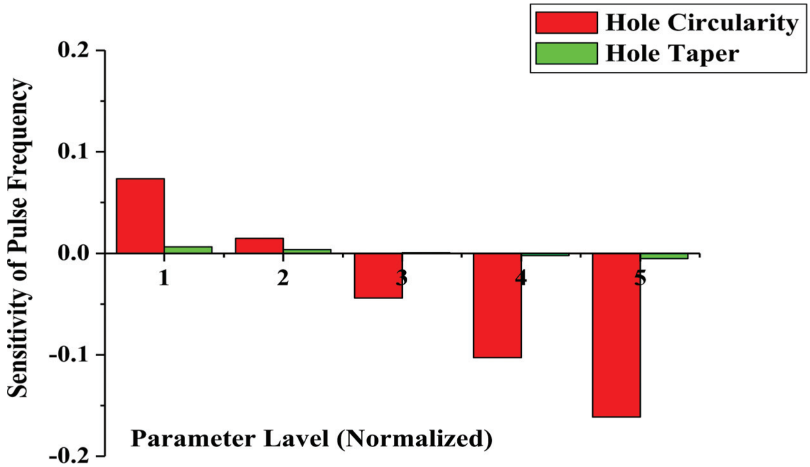

FIGURE 5
Bar chart showing sensitivity of pulse frequency in respect of machining responses.

sitivity of pulse frequency on hole circularity gradually changes from positive to negative. This because, initially when pulse frequency increases, the pulse-off time becomes shorter and the beam energy generated becomes lower, as a result the material which melts and solidifies with less disorder and produces higher circularity. After a certain limit when pulse frequency again increases, the pulse-off time becomes very short, and the material does not get time to be solidified, due to which agitation and disorder takes place in molten material during material removal process, and it results in a lower circularity.

From Figure 6 it is evident that the hole taper is positive with lower pulse width values and negative with higher pulse width values. The pulse width has positive effect on taper, and as pulse width increases, taper increases. At lower pulse widths, high concentrated beam energy causes quick penetration in the work piece thus, material removal throughout the depth is almost equal, results in less taper is formed at lower pulse width. Sensitivity of pulse width on hole circularity shows a different trend unlike hole taper. At higher pulse width due more interaction time of laser beam with workpiece, remove more material hence circularity is increased and *vice versa*.

The sensitivity of air pressure on hole taper and circularity is shown in Figure 7. The hole taper has negative air pressure sensitivities. Lower assisted air pressure is unable to compensate the excess heat generated and the top hole diameter increases. Increase in assist air pressure helps remove extra heat due to which material gets solidified at the entrance of the hole, which causes less material removal from the top surface and the hole taper decreases with increase in air pressure. But at higher levels of assist air pressure molten material is ejected from the top surface rapidly; thus, a larger hole taper is generated. The sensitivity of air pressure on circularity changes gradually

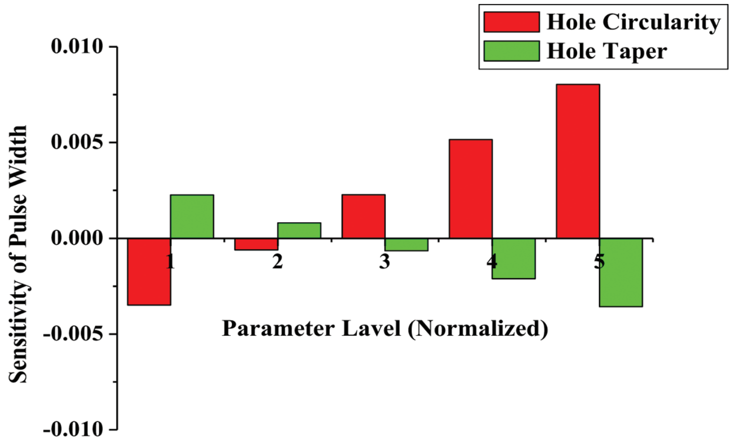

FIGURE 6
Bar chart showing sensitivity of pulse width in respect of machining responses.

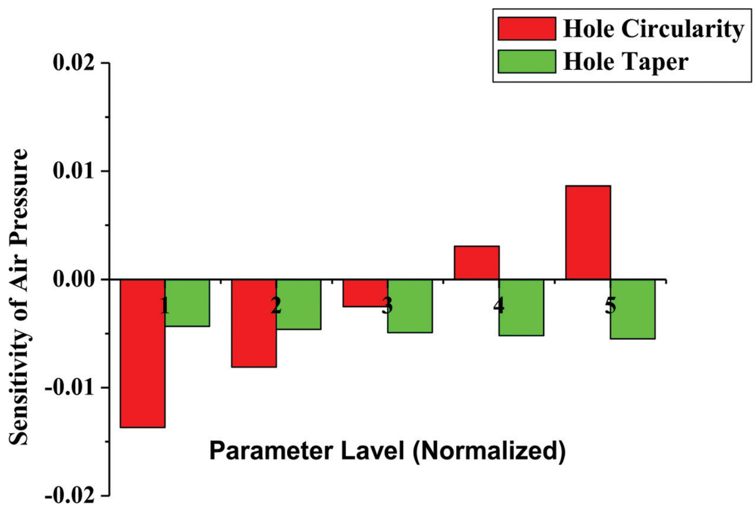

FIGURE 7
Bar chart showing sensitivity of assist air pressure in respect of machining responses.

from negative to positive. Circularity increases with increase in air pressure. Low assist air pressure removes less amount of heat from the drilling zone; however, at higher level of assist air pressure, the amount of excess heat is removed rapidly. The higher air pressure also assist to eject molten material from the drilling zone. As a result, circularity increases with increase in air pressure at high lamp current.

6 DETERMINATION OF OPTIMAL PROCESS PARAMETER SETTINGS

Figure 8 and Figure 9 show the optimization results for the maximum hole circularity and minimum hole taper based on the mathematical model developed by using Equation (2) and Equation (3). To obtain the ideal machining response the value of the weight for linear desirability function (D) is considered as 1.

It is found from Figure 8 that maximum hole circularity of 0.09515 dimension can be achieved at process parameter settings of 21.50 A lamp current, 0.4 kHz pulse frequency, 1% pulse width, and 0.6 kg/cm^2 of assist gas pressure.

It is found from Figure 9 that minimum hole taper of 0.0045 dimension can be achieved at process parameter settings of 24.50 A lamp current, 0.2 kHz pulse frequency, 1% pulse width, and 2.40 kg/cm^2 of assist gas pressure.

Multi-response optimization of maximum hole circularity with minimum hole taper are shown in Figure 10. Here, two responses have been optimized

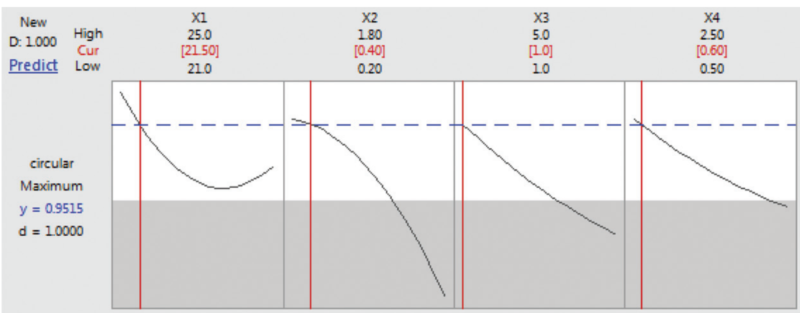

FIGURE 8
Graphs showing single objective optimization in respect of hole circularity.

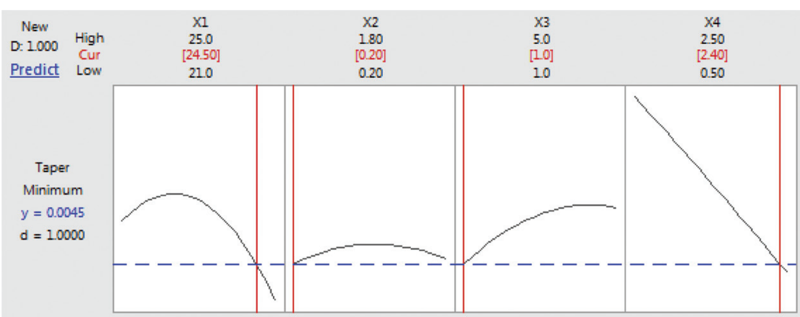

FIGURE 9
Graphs showing single objective optimization in respect of hole taper.

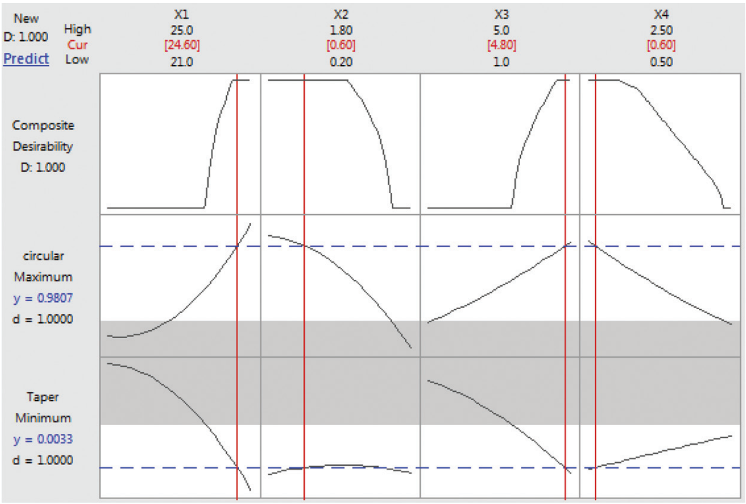

FIGURE 10
Graphs showing multi-objective optimization in respect of machining characteristics.

simultaneously. The label above composite desirability refers to the current process parameters setting and changes for moving the factor settings interactively. The label is optimal when the optimization plot is created. It is found from Figure 10 that maximum hole circularity 0.9807 along with minimum hole taper of 0.0033 dimension can be achieved at process parameter settings of 24.60 A lamp current, 0.6 kHz pulse frequency, 4.8% pulse width, and 0.6 kg/cm^2 of assist gas pressure. The value of composite desirability factor is 1 which is desired.

7 VALIDATION OF THE DEVELOPED MODEL

Five confirmation experiments were conducted with optimal process parameter settings. The actual results are calculated as the average of three measured results for each response. Results from the validation experiments and predicted values and calculated percentage error of confirmation experiments which indicate that the developed models can yield nearly accurate results. Results from the validation experiments are given in Table 8.

8 CONCLUSIONS

Pulsed Nd:YAG laser beam microdrilling of aluminium 5052 was carried out and modelled here using response surface methodology (RSM). Hole taper

TABLE 7
ANOVA analysis of hole taper.

Source	DF	Adj. SS	Adj. MS	F-Value	P-Value
Model	14	0.001279	0.000091	115.54	0.000
Linear	4	0.001031	0.000258	326.20	0.000
X_1	1	0.000883	0.000883	1117.39	0.000
X_2	1	0.000001	0.000001	1.64	0.041
X_3	1	0.000010	0.000010	12.64	0.003
X_4	1	0.000137	0.000137	173.12	0.000
Square	4	0.000133	0.000033	41.96	0.000
2-Way Interaction	6	0.000115	0.000019	24.15	0.000
Error	16	0.000013	0.000001		
Lack-of-Fit	10	0.000010	0.000001	2.17	0.178
Pure Error	6	0.000003	0.000000		
Total	30	0.001291			
S 0.0008891		R-sq 99.02%	R-sq(adj.) 98.16%	R-sq(pred.)95.29%	

TABLE 8
Confirmation test.

Lamp Current (A)	Pulse Frequency (kHz)	Pulse Width (%)	Assist Air Pressure (kg/cm^2)	Value	Hole Circularity	Hole Taper (rad)
				Predicted	0.9807	0.0033
24.6	0.6	4.8	0.6	Actual	0.9359	0.0079
				% Error	4.57	1.39

along with hole circularity which greatly influence the quality characteristics of drilled hole are considered as machining responses. The developed mathematical models are used for sensitivity analysis to determine the relative influence of different process parameters on the machining responses. Information about the critical parameters are provided by the sensitivity analysis results. All selected process parameters have a great influence on hole circularity than hole taper within the limits of drilling parameters being used. Hole taper is highly sensitive to pulse width whereas least sensitive to assist air pressure. Confirmation tests are carried out according to the parameter settings of multi-objective optimization result. Analysis of variance (ANOVA) analysis and confirmation tests results indicate at the adequacy of the developed model.

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