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ANALYSIS AND OPTIMIZATION OF PROCESS PARAMETERS IN ND : YAG LASER PERCUSSION DRILLING ON INCONEL X-750

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ABSTRACT

Nd:YAG laser provides efficient and precision drilling of variety of components particularly in aerospace applications. In this paper experimental investigation into influence of laser machining parameters pulse frequency pulse width, gas pressure on the taper and MMR(Maximum Metal Removal) of the machined hole has been performed. Response surface methodology optimal parametric analysis has been performed to determine optimal setting of the process parameters. Minimum taper has been obtained as 0.03121 when the parameters pulse frequency, pulse width, gas pressure are set at optimal parameter setting of 11Hz ,5ms and 8bar respectively. Maximum value of MMR(Maximum Metal Removal) has been obtained as 0.9472 $x10^{-3}$ g/s when the parameters pulse frequency, pulse width, gas pressure are set at optimal parameter setting of 14Hz ,5ms and 8bar respectively. Analysis has also been carried out for multi-optimization of both the responses taper and MMR. Also the variation of material composition in recast layer and heat affected zone(HAZ) has been studied.

Keywords: Laser percussion drilling, taper, RSM, Inconel X750 and MMR

1. Introduction

Laser beam machining is a thermal energy based process in which high energy density laser beam is focused on a work surface which absorbs heat and transforms the metal into a molten, vaporized and chemically changed state which is removed by flow of high pressure assisted gas jet ejecting the molten metal outwards[2]. The schematic of LBM is shown in the figure 1. Nd:YAG laser has the following advantage over CO 2 laser,it has high laser beam intensity at low mean beam power, small kerf width and narrow heat affected zone. S.Bandyopadhyay, J.K.SarinSundar, G.Sundararajan, S.V.Joshi [1] have investigated the geometrical features and metallurgical characteristics of Nd:YAG laser drilled holes in thick IN718 and Ti-6Al-4V sheets. Avanish Kr. Dubey, VinodYadava [2] have done an experimental study on the process parameters and quality characteristics of Nd:YAG laser beam machining with the aid of DOE(Design of Expirements) and without the aid of DOE and differentiated and discussed the conclusions. Arindam Ghosal, Alakesh Manna [3] have optimized the ytterbium fiber laser parameters during the machining of Al/AL2O3-MMC using response surface methodology. A.S.Kuar, B.Doloi, B.Bhattacharyya [4] have modeled and analyzed the characteristics during micro-drilling of Zirconia (ZrO2) using pulse Nd:YAG laser. T. Beck, G. Bostanjoglo, N. Kugler, K.Richter, H.Weber [5] have experimented the effective applications of novel materials for aircraft industry using three approaches to laser drilling, namely, single pulse, percussion and trepanning. B.S.Yilbas [6] has shown that the extent of taper formation during the laser percussion drilling of thin sections can be significantly reduced by suitable control of laser variables like focal position, pulse energy, pulse width and pulse frequency can effectively control recast layer formation inside the drilled hole. C.Y.Yeo, S.C.Tam, S.Jana.M.W.S.Lau [7] suggested that high peak power and pressure, preferably obtained by appropriate control of pulse energy and pulse duration is required to suppress the formation of the recast layer. D.K. Low, L. Li, A.G. Corfe [8] observed that Spatter constitutes to one of the main defects in laser drilling which is formed when the ejected material is not completely expelled but re-solidifies and adheres around the periphery of the hole. The extent of spatter formation is mainly observed at the entrance side of the hole, was found to be consistently more in case of thicker materials. This is because expulsion of great amount of material is necessary during drilling of thick sections as compared to thin ones. The work by G. Bostanjoglo, T. Pachale, T. Beck, H. Weber [9] on laser drilling of stainless steel has also shown that the use of

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relatively more reactive oxygen in place of compressed air, under identical gas pressure, yields smaller entrance diameters. D.K. Low, L. Li, A.G. Corfe, P.J. Byrd, [10] have accomplished several methods involving application of anti-spatter coatings as well as drilling in transparent media to minimize spatter formation.

2. Experimental Planning

It is always desired to know the effect of variation of input parameters on process performance in order to achieve the goal of better product quality. LBM being a non-conventional machining process requires high investment and offers poor efficiency (below 1%). So, high attention is required for better utilization of resources. The experiment was performed on INCONEL X 750 alloy of thickness 6.85mm , the parameter pulse height is kept constant at 30% of maximum amplitude and the effect of variation of process parameters pulse frequency, pulse width and gas pressure on the drilled holes were examined by measuring the quality attributes of the hole such as taper and MMR. Laser drilling experiments were performed with a 400 W Nd: YAG Laser (Model JK 704) from GSI Lumonics UK, emitting 1.06 μm wavelength with fixed beam delivery. The focus was set on the surface of the material. The laser beam was focused with a 120mm focal length lens giving a spot size of approximately 0.24 mm diameter. A co-axial gas nozzle assembly was used to provide an assist gas for drilling. Oxygen gas at various pressures was employed during drilling. The laser drilling experiments is conducted in two stages to achieve the goal of the study. Initial experiments are conducted to establish the parametric regimes based on pulse frequency, pulse width and gas pressure so that a through hole is obtained. In the second stage, detailed experiments were carried out within the processing regimes to access the influence of operating variables. The diameters of the holes were measured using a Video Measuring Machine, OPUS C-2010. Each hole entry and exit diameter is measured using eight probe circle measurement technique in order to accurately measure the hole dimensions. The thickness of the hole was measured using a vernier caliper.

A well designed experimental plan can reduce the total number of experiments Central composite design with three levels is one of those means. Response surface modeling has been made to establish the mathematical relationship between the response and various parameters.

The duration of drilling is computed based on the shutter open and close time, although this does not indicate the actual machining time however this can be approximated for studying the variation of MMR with the process parameters. The opening and closing of the stutter actuates the laser drilling process spontaneously. Hence, the duration of time interval between the stutter opening and closing gives the laser drilling duration.

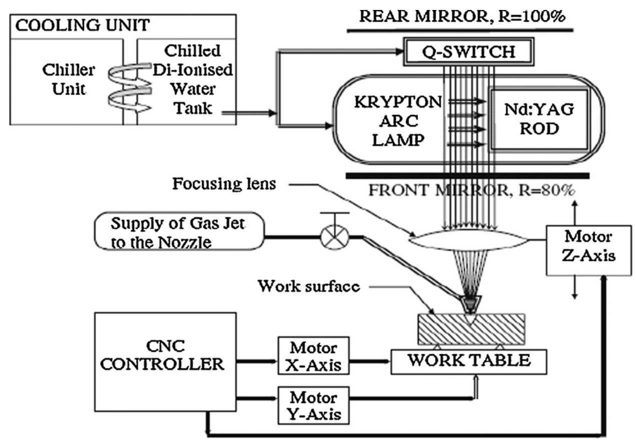

Fig. 1 Schematic of Nd:YAG Laser System

Table: 1 Properties of INCONEL X-750

Property	Value
Density	8.303 g/cm^3
Melting range	1393 – 1427 °C
Thermal expansion	12.1 – 16.2 x 10^{-6} / °C
Specific heat capacity	0.42 – 0.54 J/g K
Tensile strength	1170 - 1380 M Pa
Tensile strength, Yield	850 MPa
Brinell hardness	313 – 400 BHN
Thermal conductivity	16.9 – 35.3 W/m K
Elongation at break	30 %

Taper = (D-d)/2t (1)

Taper radian = [tan^(-1)((D-d)/2t)](π/180) (2)

MMR = volume of material removed x density/duration of drilling (3)

Volume=H/3(a1+a2+$\sqrt{a1 * a2}$) (4)

The mathematical modeling of response for process parameters are calculated based on second order differential equation given below.

$$Y = b_0 + b_1X_1 + b_2X_2 + \ldots\ldots + b_{11}X_1^2 + b_{22}X_2^2 + \ldots + b_{12}X_1X_2 + \ldots + b_{n-1,n}X_{n-1}X_n. \quad (5)$$

Table: 3 Experimental Run Showing Process Parameters and Responses

Std	Run	A, Hz	B, ms	C, bar	Taper	MMR x10^{-3}, g/s g/s
15	3	13	5.5	10	0.04379	0.797
18	7	13	5.5	10	0.0447	0.852
20	13	13	5.5	10	0.0457	0.833
16	18	13	5.5	10	0.0461	0.778
19	19	13	5.5	10	0.0442	0.903
17	20	13	5.5	10	0.04537	0.757
10	4	15	5.5	10	0.04014	0.917
9	9	11	5.5	10	0.0424	0.4676
13	11	13	5.5	8	0.03635	0.88
12	14	13	6	10	0.05116	0.6496
14	16	13	5.5	12	0.03956	1.1033
11	17	13	5	10	0.04627	0.8115
4	1	15	6	8	0.03985	0.7995
7	2	11	6	12	0.04839	0.2905
8	5	15	6	12	0.03116	0.995
2	6	15	5	8	0.04116	1.222
5	8	11	5	12	0.04773	0.5131
1	10	11	5	8	0.03197	0.4546
6	12	15	5	12	0.0451	0.9877
3	15	11	6	8	0.04824	0.2363

3. Analysis of Variance and Model Fitment Test

Analysis of variance and corresponding F-test and P-test is carried out to check the adequacy of the mathematical model for taper and MMR. Table 4 shows the results of analysis of variance for MMR. Developed second order regression model is significant for taper as F-value 25.88 of model is significant and the lack of fit F-value of 4.39 is insignificant. Values of "P-value" less than 0.050 indicates that the model terms are significant.

Table 5 gives the results of analysis of variance for MMR. Model F value of 31.54 for MMR is significant and the lack of fit is insignificant. Also R-Squared and Adj R-Squared value are close to unity for both the responses, Adeq precision value give the signal to noise ratio and Adeq precision value of 18.092 and 19.919 for Taper and MMR respectively implies and adequate signal.

Table: 4 Analysis of variance for MMR

Source	Sum of Squares	Df	Mean Square	F Value	P – value Prob> F
Model	0.64	9	0.071	31.54	<0.0001
A	0.43	1	0.43	191.19	<0.0001
B	0.065	1	0.065	29.19	0.0003
C	0.0059	1	0.0059	2.63	0.1356
AB	0.015	1	0.015	6.84	0.0258
AC	0.0024	1	0.0024	1.09	0.3215
BC	0.0063	1	0.0063	2.81	0.1245
A^2	0.041	1	0.041	18.51	0.016
B^2	0.017	1	0.017	7.46	0.0212
C^2	0.0082	1	0.0082	3.66	0.0847
Residual	0.022	10	0.0022		
Lack of fit	0.018	5	0.0036	4.67	0.0580
Pure Error	0.0039	5	0.00079		
Cor Total	0.66	19			

Table: 5 Results of ANOVA for taper and MMR

	Taper	MMR
Model F value	25.88	31.54
Lack of fit F value	4.39	4.67
R – Squared	0.9588	0.9660
Adj R – Squared	0.9218	0.9353
Pred R –Squared	0.7379	0.7198
Adeq Precision	18.092	19.919

4. Parametric Influence on Response

4.1 Analysis of parametric influence on Taper

Figure 2 shows the effect of pulse width and pulse frequency on taper of the hole keeping gas pressure 10 bar and pulse height 30% constant. It is observed that the taper increase with increase in pulse width for pulse frequency in the range 11-12 Hz. The taper decreases with increase in pulse width for pulse frequency range 14-15 Hz, however the gradient of later is smaller. Maximum taper is observed for higher pulse width and subsequently decreases with increase in pulse frequency this due to fact that with increase in pulse frequency, the number of pulses increases this allows for easy penetration until the depth of the hole. Also Higher pulse width generates low thermal energy concentration where the molten material is removed from the top surface during penetration into remaining thickness eroding the top surface, which produces large taper.

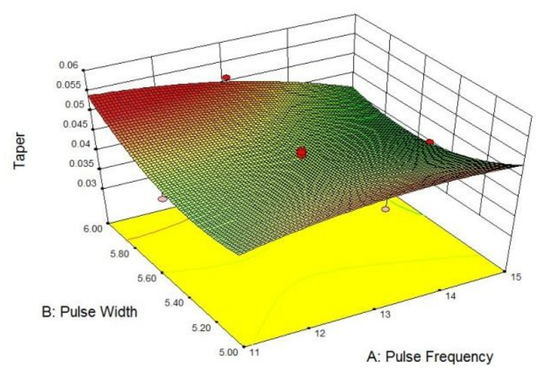

Fig. 2 Response Surface Plot of Taper with Pulse Width and Pulse Frequency.

Figure 3 shows the effect of pulse width and gas pressure on Taper of the machined hole keeping pulse frequency 13 Hz and pulse height 30% as constant from the figure the taper increases with increase in pulse width when gas pressure is 8 bar. At gas pressure value of 12 bar, taper decreases initially with increase in pulse width up to 5.5 ms and then increases with increase in pulse width. Higher gas pressures and low pulse width gives high pulse energy concentration, hence taper decreases up to 5.5 ms, however at higher pulse width pulse energy is low hence higher gas pressure increases erosion during initial phase removal of melt form top surface where through hole is not formed therefore taper of the hole increases with increase in pulse width.

Taper = -0.14742 + 0.042830 * Pulse Frequency – 0.13499 * Pulse Width +0.056883 * Gas Pressure – 4.0225E-003 * Pulse Frequency * Pulse Width – 6.4562E-004 * Pulse Frequency * Gas Pressure – 3.53000E-003 * Pulse Width * Gas Pressure – 5.89091E-004 * Pulse Frequency^2 + 0.020355 * Pulse Width^2 – 1.41784E-003 * Gas Pressure^2

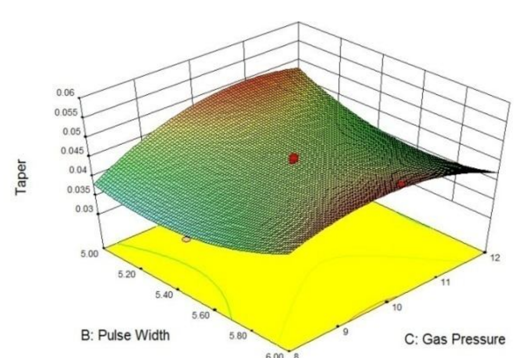

Fig. 3 Response Surface Plot of Taper with Pulse Width and Gas Pressure

Figure 4 shows the effect of pulse frequency and gas pressure on taper of the machined hole keeping pulse width as 5.5 and pulse height 30% as constant. It is observed that maximum taper is obtained for gas pressure 10 bar and pulse frequency 13 Hz. Taper of a hole increases with increase in gas pressure up to 11 bar for various setting of pulse frequency and then starts to decrease, this is because with higher gas pressure greater material is pushed towards the hole exit and hence enlarging the exit hole. Variation of taper with pulse frequency for particular gas pressure is little, however taper tends to decrease with increase in pulse frequency expected in higher values of gas pressure.

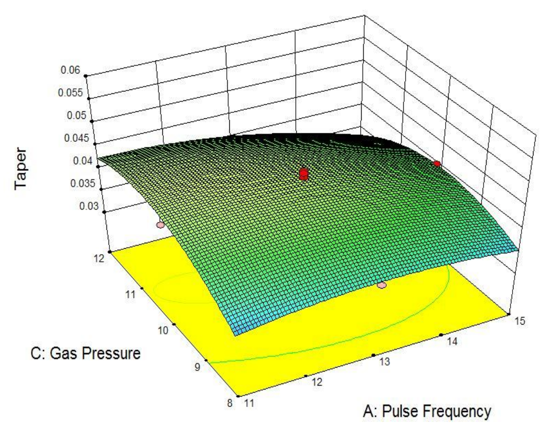

Fig. 4 Response Surface Plot of Taper with Pulse Frequency and Gas Pressure

4.2 Analysis of parametric influence on MMR

Figure 5 shows the effect of pulse width and pulse frequency on MMR keeping gas pressure 10 bar and pulse height 30% as constant. It is observer that MMR increases linearly with increase in pulse frequency at different settings of pulse width this is more likely as increase in pulse frequency increase number of pulses that remove material in smaller duration hence material removal rate increases linearly with increase in pulse frequency. Variation of MMR with pulse width for different setting of pulse frequency is almost constant, however slight increase in MMR is observed with decrease in pulse width as high pulse energy facilitates rapid melting and vaporization of metal.

Figure 6 shows effect of gas pressure and pulse frequency on MMR keeping pulse width 5.5 and pulse height 30% constant. It is observed that MMR increases almost linearly with increase in pulse frequency at different settings of gas pressure. Also MMR increases with increase in gas pressure, this is because increase in gas pressure increases the rate of removal of molten metal and fresh new metal is exposed which then melts with new pulse. This increases the amount of material removed.

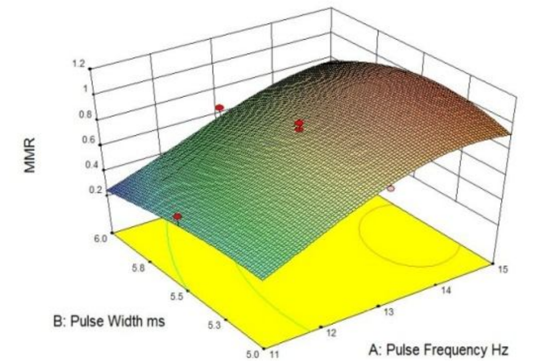

Fig. 5 Response Surface Plot of MMR with Pulse Width and Pulse Frequency

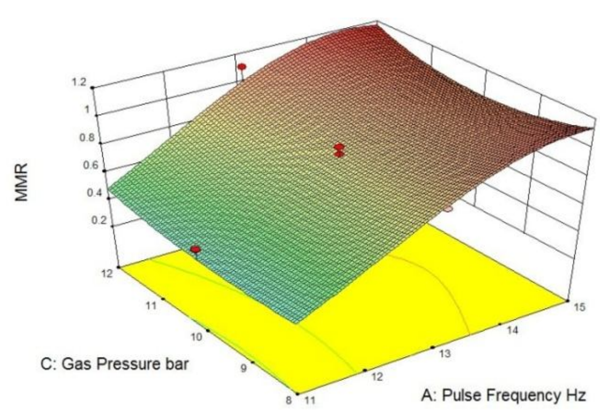

Fig. 6 Response Surface Plot of MMR with Gas Pressure and Pulse Frequency

Figure 7 shows effect of gas pressure and pulse width on MMR keeping pulse frequency 13 Hz and pulse height 30% constant. It is observed that MMR increases with increase in gas pressure for different setting of pulse width. Maximum MMR is observed at lower pulse width setting. Increase in MMR with gas pressure is already explained. Shorter pulse width results in high peak beam power which increases the thermal energy. Beam with high peak energy facilitated quick melting and vaporization of material thus increasing the maximum material removal. Larger pulse width reduces concentration on pulse energy in short duration and thus reducing the peak pulse energy and results in lesser material removal.

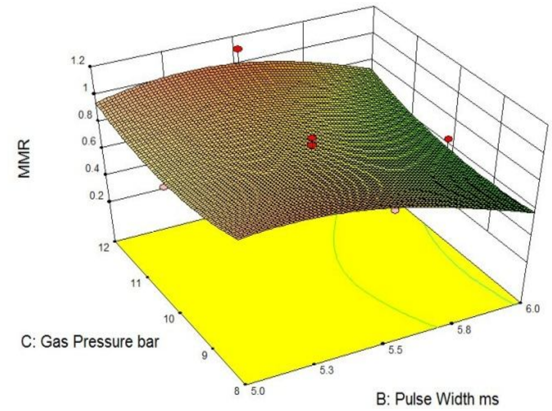

Fig. 7 Response Surface Plot of MMR with Pulse Width and Gas Pressure

Log_{10} (MMR) = - 9.80793 + 0.70483 * Pulse Frequency + 2.41983 * Pulse Width – 0.35866 * Gas Pressure + 0.043771 * Pulse Frequency * Pulse Width – 4.36552E-003 * Pulse Frequency * Gas Pressure + 0.028070 * Pulse Width * Gas Pressure – 0.030708 * Pulse Frequency^2 -0.31194 * Pulse Width^2 + 0.013659 * Gas Pressure^2

5. Optimization

From the developed second order response equation optimal parametric setting for minimum Taper and maximum MMR can be obtained. The constraints table 6 shows the region of optimization required, here we concentrate on obtaining minimum taper for various parameters. Hence goal for taper is set minimum and the other parameters are kept within the range given in the table. A total of 15 solutions were obtained and the solution with the maximum desirability is selected. Solution 3 provides minimum taper of 0.0312201. Similarly, based on constraint for maximum MMR the obtained value is 0.9472 $x10^{-3}$ g/s.

Table 7 shows the variation of material composition in parent material, HAZ and recast layer. From the table there is significant amount of oxygen present in Recast layer confirming the presence of oxides. Figure 8 shows the presence of oxide inclusions and cracks inside the hole. Also there is variation of material composition in HAZ where there is significant percentage of carbon and oxygen.

Table: 6 Constraint Table for Minimum Taper

Name	Goal	Lower Limit	Upper Limit
A – Pulse frequency	Is in range	11	15
B – Pulse width	Is in range	5	6
C – Gas pressure	Is in range	8	12
Taper	Minimize	0.025	0.038
MMR	Is in range	0.4	1.3

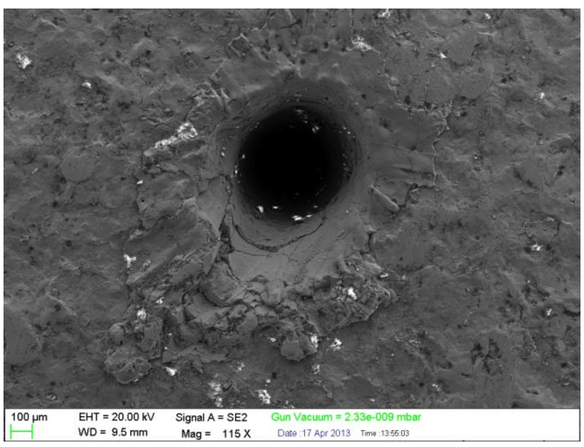

Fig. 8 SEM Image of the Hole Showing Spatter

Table: 7 EDS Results of Different Regions of Laser Drilled Material

Material (%wt)	Ni	Cr	Fe	Ti	Si	C	O
Parent material	70.39	16.41	8.732	2.16	0.21	0.0001	-
HAZ	63.88	13.78	7.68	2.11	0.22	4.64	5.78
Recast layer	20.65	5.07	4.50	0.83	8.31	22.82	35.57

Figure 9 depicts the recast layer along with defects such as cracks and oxide inclusions, resulting from the usage of oxygen as the assist gas. Figure 10 shows low magnification microstructure of the recast layer and HAZ in the laser drilling of INCONEL X 750.

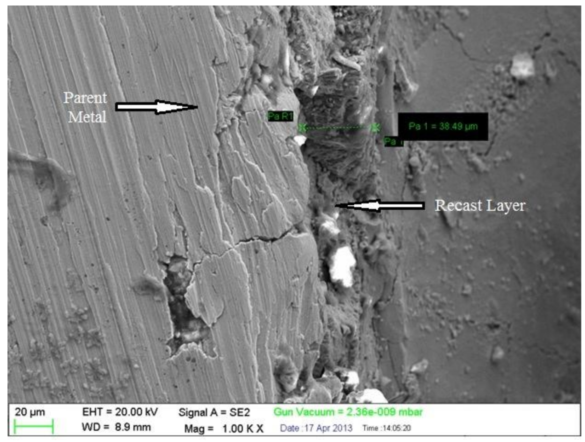

Fig. 9 SEM Image of Hole Cross Section Showing Recast Layer and Cracks

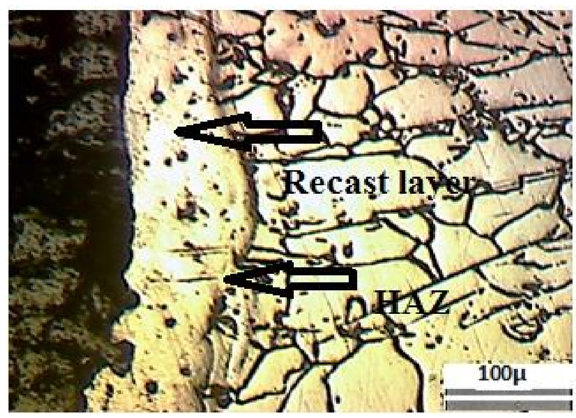

Fig. 10 Microstructure Showing Recast Layer and HAZ

7. Conclusions

The following conclusions are derived from this investigation:

i. Parameters pulse frequency and pulse width are identified as significant for taper of the micro-hole.
ii. Parameters pulse frequency, pulse width and gas pressure are identified significant for MMR.
iii. Results show that high pulse frequency, low pulse duration and low gas pressure gives holes with lesser taper.
iv. Results show that high pulse frequency, low pulse width and high gas pressure gives higher material removal rate.
v. Optimal parameter setting for minimum taper is pulse frequency 11Hz, pulse width 5.0ms and gas pressure 8 bar.

vi. Optimal parameter setting for maximum MMR is pulse frequency 14Hz, pulse width 5.12ms and gas pressure 8 bar.

vii. Optimal parameter setting for maximum MMR and minimum taper is pulse frequency 15Hz, pulse width 5.7ms and gas pressure 12 bar.

Nomenclature

Symbol	Meaning	Unit
D	Hole entry diameter	mm
d	Hole exit diameter	mm
t	Thickness of the workpiece	mm
H	Height of hole	mm
A1	Area of top hole surface	mm^2
A2	Area of bottom hole surface	mm^2

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