Modeling of hole geometrical features in laser drilling of AISI316L sheet

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ABSTRACT

Micro-drilling of AISI316L is very challenging task. Unconventional machining process may be used for such type of operation. Laser beam drilling is a best for micro drilling. High thermal energy and converging-diverging property of laser beam affects the quality of laser drilled holes. In present work Nd:YAG laser beam has been used and investigate effects of laser input parameters on responses. To minimize number of experiments, get extreme information for experimental trials. Central composite rotatable design approach has been adopted. Analysis of variance is used to find reliable input parameters, are affecting responses. From this paper, it is found that current and gas pressure are significant for hole circularity at top. Current and pulse frequency are significant for bottom side circularity. Current and cutting speed are significant parameter for hole taper.

Key words: LBD; ANOVA; RSM; AISI316L; Hole Taper; Hole Circularity.

INTRODUCTION

Micro-drilling is very difficult task for modern materials. Stainless steel material AISI316L is one of them and has many applications in medical, automotive, aeronautics and aerospace industries. Because AISI316L material is having unique material properties like as high thermal conductivity, high corrosion resistance, and high strength etc. AISI316L is bio-compatible material., It is used as orthopaedic material., It also widely used for biomedical applications and as well as bio-industries [E. Audouard et al., 2017 & A. Bharatish et al., 2013].

Now a days, laser drilling is used in medical industries, automobile sector and many more industries. Its unique properties like no tool wear, no contact between tool and work piece, low wastage of materials, precise hole features and micro machining etc, make it special from other conventional machining process [A. Cekic et al., 2014]. Laser beam is highly intensive and monochromatic beam. Laser beam is used as a machine tool for creating hole during laser drilling. During process, laser beam is focused on surface of material, kinetic energy of laser beam converts in heat energy and melting process takes place. Now molten material is removed by process of evaporation. Remaining unwanted material is removed by blown of highly assist gas pressure. Finally, precise drilled hole take place on work piece [I. Choudahry et al., 2012 & A. Dubey et al., 2008].

Laser beam machining process is generally used for machine advanced material like titanium, Ni based alloy and AISI316L etc. Laser cutting has been used to machining of high-speed steel and AISI316L. Authors have seen kerf width formation with effect of cutting speed and power input on steel materials. Various researchers have studied effect of parameters as pulse frequency (PF), power, gas pressure (GP) and cutting speed (CS) in formation of kerf width and heat affected zone on general metals [G. Gautam et al., 2018, K. Ghany et al., 2005, R. Goyal et al., 2016 & A. Hascalik et al., 2013].

Few researchers found kerf width increase with improve laser power but decrease it while increasing cutting speed. To cut of 4130 steel through laser, PF plays major role to reduce heat affected zone (HAZ) and kerf width (KW) [S. Kumar et al., 2006]. HAZ decrease while increase laser power to machining of SS304. KW reduce if increased CS [A. Lamikiz et al., 2005].

Researchers have seen the effect of GP and PF on recast layer formation. Also examined circularity of hole geometrical features during laser trepan drilling in IN718, Ti alloy, stainless steel etc. Researchers have been used CO_2 and Nd: YAG laser to perform drilling operations and saw the effect of PF, GP, Current (C), pulse width, pulse mode etc on hole geometrical features like circularity and hole taper (HT) [D. Montgomery et al., 2015]. Researchers prepared scientifically designed experimental run using orthogonal array or CCD (central composite design) based on considering number of independent variables. Researchers also used hybrid approach to optimize their responses like HAZ & KW for laser cutting and HT for laser drilling. Artificial intelligence tools like fuzzy logic, & genetic algorithm (GA) are used successfully to accomplish work for modelling and optimization of responses. Based on literature review, present work is study geometric features of drilled hole of diameters 1 mm on AISI316L sheet. All Experiments have been performed on pulsed Nd:YAG laser beam system. Four input parameters (GP, C, CS & PF) and their effect on three responses have been decided. These responses are hole taper (HT), hole circularity at entrance (Cent) and exit sides (Cexit) of hole. There hundreds experimental combination are possible with four input parameters. To minimize number of experiments with maximum information. CCD approach has been chosen. Minitab software has been used to prepare design of experiment. Experimental data has been used to developed empirical model.

EXPERIMENTAL DESIGN AND SETUP LAYOUT

Response surface methodology (RSM) is a statistical method of design of experiment. This method has been used for modeling and optimization purpose. Generally, this method is used for optimize engineering problems. There are many experimental methods are in RSM, central composite design (CCD) is one of them. This design is most effective design over other experimental design. In CCD, second order regression model is prepared [A. Pandey et al., 2013]. For CCD, numbers of experiments are finalized with below mentioned formula in equation 1.

$$N = K^2 + 2K + C \quad (1)$$

Where, N = number of experiments, K = number of input parameters (4), & C= number of central run (7). The total number of experiments (N) are 31 [M Radovanovic et al., 2011].

Table 1. Chemical Composition of AISI316L Sheet.

Material	Cr	Ni	Mo
% Composition	17.06%	10.17%	2.1%

A 500 W Nd:YAG laser has been used. Its peak power is 5 kW and wavelength 1064 nm. AISI316L sheet of 1.8 mm thickness has been used for drilling operation. AISI316L plate of dimension is 150 mm*100 mm*1.8 mm. Density (g/cm^3), specific heat (J/kg^0K), melting point temperature (^0C), thermal conductivity (W/m^0K) and coefficient of thermal expansion ($1 / {}^0C$) of AISI316L plate are 8, 500, 1440, 16.3 and 15.9 respectively. Chemical composition of work material is shown in Table 1. Input parameters' range have been decided on the basis of trial-based experiments for through hole of 1 mm diameter. Range of input parameters with levels are given in Table 2. Due to some experimental limitation, not possible to consider all values of input parameters. In this situation, nearest values have been preferred for input parameters [N. Rajaram et al., 2003]. In presenting work, all input parameters values for their level are very near to theoretical values.

Table 2. Input parameters and their levels.

Symbol	Input Parameters (Abbreviations)	Unit	Level				
			-2	-1	0	1	2
p_1	GP	{kg/cm^2}	6	7	8	9	10
p_2	C	{Amp}	150	175	200	225	250
p_3	CS	{mm/min}	10	20	40	60	80
p_4	PF	{Hz}	8	9	10	11	12

EVALUATION OF DRILLED HOLE QUALITY CHARACTERISTICS

Hole diameter

Hole dimeter has been measured from four different side. It has been measured along circumferentially of hole at interval of 45^0. Hole dimeter has been measured by Moticam series stereo microscope. After that, average has been taken of four diameters d_1, d_2, d_3 and d_4 for hole as shown in Figure 1 [Saini et al., 2018]. Same measurement process has been followed for all experiments. Hole diameter has been measured for top side and bottom side also. Microscopic image of drilled hole has been shown in Figure 1 and Figure 2.

Hole Circularity (Cent, Cexit) and Hole Taper (HT)

Laser drilled hole is created by using thermal energy of laser beam. Laser drilled hole boundary is not be perfect circular. Hole circularity at bottom and top side are measured by given formula in equation 2 and equation 3. Drilled holes are not perfectly circular. Due to this reason in the case of through hole, there will be some difference between top and bottom side diameter. It is measured by formula given in equation 4. Hole taper is depending upon sheet thickness [Saini et al., 2018].

$$Cent = (D_t)min \ / \ (D_t)max \qquad (2)$$

$$Cent = (D_b)min \ / \ (D_b)max \qquad (3)$$

$$H_T = \frac{180}{\pi}\left\{Tan^{-1}\left(\frac{D_{ent}-D_{exit}}{2t}\right)\right\} \qquad (4)$$

Where, D_t= top side diameter, D_b= bottom side diameter, D_{ent}= Top side diameter, D_{exit}= bottom side diameter & t= sheet thickness.

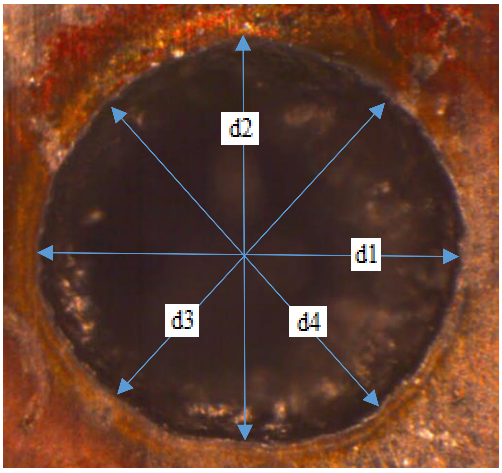

Figure 1. Microscopic image of top diameter.

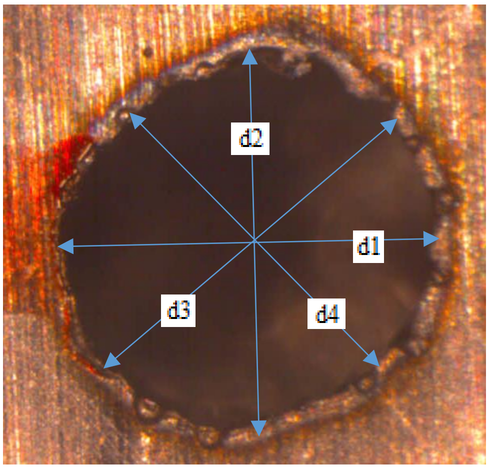

Figure 2. Microscopic image of bottom diameter.

REGRESSION MODEL

RSM is a mathematical tool that can be used to make a best model for multi-parameters in experimental data and prepare an optimum experiment design. RSM is trustful arithmetic technique for many applications. A mathematical relation has been prepared between input parameters and responses. That will help to know behavior of process parameters on response. General second order regression equation as given in equation 5 [R. Goyal et al., 2016].

$$y_k = \alpha_0 + \sum_{i=1}^{n} \alpha_i p_i + \sum_{i=1}^{n} \alpha_i p_{ii}^2 + \sum_{i=1}^{n} \sum_{j=n+1}^{n} \alpha_{ij} p_i p_j \qquad (5)$$

Where ‘α’ are regression coefficients. ‘n’ is number of input parameters. y_k is response [S. Saini et al., 2018]. After checking acceptability of parameters as values are given in Table 2. Second order regression equations are developed for responses Cent, Cexit & HT accordingly. General second order regression equations as given in equation 6, 7 & 8 for responses Cent, Cexit & HT respectively in uncoded units for AISI316L as follows:

$$Cent = -1.672 + 0.2896\,p_1 + 0.00989\,p_2 + 0.00384\,p_3 + 0.0632\,p_4 - 0.01210\,p_1^2 - 0.000015\,p_2^2 - 0.000030\,p_3^2 - 0.00053\,p_4^2 - 0.000332\,p_1*p_2 + 0.000131\,p_1*p_3 - 0.00302\,p_1*p_4 - 0.000007\,p_2*p_3 - 0.000071\,p_2*p_4 - 0.000071\,p_3*p_4 \quad (6)$$

$$Cexit = 1.10 - 0.071\,p_1 + 0.01075\,p_2 - 0.00797\,p_3 - 0.190\,p_4 + 0.00093\,p_1^2 - 0.000025\,p_2^2 - 0.000002\,p_3^2 + 0.00343\,p_4^2 - 0.000579\,p_1*p_2 + 0.001247\,p_1*p_3 + 0.01369\,p_1*p_4 + 0.000057\,p_2*p_3 + 0.000298\,p_2*p_4 - 0.001473\,p_3*p_4 \quad (7)$$

$$HT = 36.7 - 2.26\,p_1 - 0.2862\,p_2 + 0.1275\,p_3 + 1.95\,p_4 - 0.0360\,p_1^2 + 0.000458\,p_2^2 - 0.000411\,p_3^2 - 0.0330\,p_4^2 + 0.01644\,p_1*p_2 - 0.01654\,p_1*p_3 - 0.00067\,p_3*p_4 \quad (8)$$

MODEL VALIDATION

Theoretical Validation

S-value and R-value are calculated for theoretical validation of any model. These values are given in Table 3 for individual model. If correlation coefficient's value (R-value) is more than 0.9, then predicted data will be acceptable. In present case, R-value is more than 0.9 for each model. Now, data given in Table 2 is well fitted for all responses [R. Goyal et al., 2016 & A. Hascalik et al., 2013].

Table 3. Regression analysis of developed model.

Model Summary	S	R-sq	R-sq (adj)
Cent	0.0088	90.70%	82.57%
Cexit	0.0269	93.22%	87.29%
HT	0.2817	94.93%	90.50%

Analysis of variance (ANOVA) has been used to test capability of models. Its results have been shown for all models in Table 4. P-values is less than 0.5 for all three models. F-ratios is also calculated for source of regressions. F-ratios are 11.21, 15.72 and 21.41 for Cent, Cext and HT models, respectively. F-ratios for responses are more than critical F-ratio. Confidence level is 95% [W. Tiffany et al., 1985]. So, developed experimental relations for all parameters are significant. It also acceptable for prediction of responses value.

Table 4. ANOVA result for Responses.

Source	**DF**	**F-Value**				**P-Value**	
		Cent	**Cexit**	**Cent**	**Cexit**	**Cent**	**Cexit**
Regression	14	11.15	15.72	11.15	15.72	11.15	15.72
Linear	4	15.56	3.22	15.56	3.22	15.56	3.22
Square	4	27.13	2.62	27.13	2.62	27.13	2.62
2-Way Interaction	6	2.92	12.51	2.92	12.51	2.92	12.51
Error	16						
Lack-of-Fit	9	1.63	2.98	1.63	2.98	1.63	2.98
Pure Error	7						
Total	30						

Significant Factor Analysis

ANOVA technique has been used to find out significant input parameters for the responses. Results have been shown in Table 5. Gas pressure and current are significant for Cent. Current and pulse frequency are significant for Cexit. Current and cutting speed are significant for HT.

Table 5. p-values of input parameters for responses.

Process Parameters	**Cent**	**Cexit**	**HT**
Gas Pressure	**0**	0.601	0.125
Current	**0**	**0.041**	**0**
Cutting Speed	0.085	0.231	**0.035**
Pulse Frequency	0.18	**0.032**	0.195

Experimental Validation:

Experimental Validation: Experimental data will be compared with the predicted regression model. Mean prediction percentage error (MPPE) will be found out for all the responses.

Table 6. Mean prediction error for different responses.

Exp. No	Input parameters				Cent			Cext			HT		
	p_1	p_2	p_3	p_4	Pred.	Expe.	% error	Pred.	Expe.	% error	pred.	Exp.	% error
1	7	175	20	11	0.93	0.92	1.29	0.90	0.93	3.49	7.95	7.57	5.01
2	9	175	20	11	0.95	0.94	0.69	0.93	0.91	2.61	7.05	6.81	3.54
3	7	225	20	11	0.96	0.95	1.48	0.95	0.95	0.35	5.27	5.32	1.03
4	9	225	20	11	0.95	0.93	1.67	0.93	0.96	2.96	6.01	5.84	2.92
5	7	175	60	11	0.95	0.93	1.71	0.67	0.65	3.44	8.47	8.53	0.73
6	9	175	60	11	0.97	0.96	1.14	0.81	0.84	3.77	6.25	5.85	6.76
7	7	225	60	11	0.96	0.94	2.57	0.84	0.86	2.08	6.26	5.92	5.78
8	9	225	60	11	0.96	0.94	1.70	0.92	0.92	0.02	5.68	5.73	0.89
9	7	175	60	11	0.95	0.93	1.71	0.67	0.67	0.36	8.47	8.61	1.70
10	9	175	20	9	0.92	0.91	1.46	0.88	0.90	1.70	7.00	6.90	1.48
11	7	225	20	9	0.94	0.91	2.85	0.93	0.93	0.08	5.80	5.75	0.86
12	9	225	20	9	0.93	0.92	1.03	0.85	0.90	5.25	6.60	6.35	3.98
13	7	175	60	9	0.92	0.89	2.39	0.80	0.80	0.50	8.41	8.14	3.37
14	9	175	60	9	0.95	0.94	1.44	0.88	0.89	1.44	6.25	6.20	0.81
15	7	225	60	9	0.94	0.92	2.36	0.94	0.97	3.51	6.84	7.09	3.47
16	9	225	60	9	0.95	0.92	2.79	0.96	0.96	0.08	6.33	6.26	1.04
17	6	200	40	10	0.92	0.91	0.88	0.87	0.91	4.71	7.26	7.16	1.44
18	10	200	40	10	0.94	0.91	2.92	0.93	0.94	1.43	5.84	6.10	4.13
19	8	150	40	10	0.93	0.92	0.65	0.76	0.78	2.34	9.15	9.41	2.81
20	8	250	40	10	0.95	0.92	3.31	0.90	0.94	4.30	6.54	6.42	1.83
21	8	200	10	10	0.94	0.91	3.01	0.94	0.94	0.44	6.24	6.61	5.63
22	8	200	80	10	0.94	0.93	1.38	0.83	0.88	5.61	6.16	6.12	0.65
23	8	200	40	12	0.99	0.97	2.45	0.88	0.93	4.89	6.30	6.51	3.29
24	8	200	40	8	0.95	0.94	1.15	0.93	0.94	1.14	6.84	6.77	0.96
25	8	200	40	10	0.98	0.95	2.71	0.89	0.90	0.76	6.70	6.62	1.17
26	8	200	40	10	0.98	0.96	1.64	0.89	0.93	3.96	6.70	6.41	4.49
27	8	200	40	10	0.98	0.96	1.64	0.89	0.89	0.36	6.70	6.80	1.51
28	8	200	40	10	0.98	0.95	2.71	0.89	0.93	3.96	6.70	6.66	0.56
29	8	200	40	10	0.98	0.97	0.59	0.89	0.90	0.76	6.70	6.91	3.07
30	8	200	40	10	0.98	0.97	0.59	0.89	0.89	0.36	6.70	6.49	3.20
31	8	200	40	10	0.98	0.96	1.64	0.89	0.93	3.96	6.70	6.47	3.52

MPPE value is calculate by formula given equation 9:

MPPE= (Experimental value-Predicted value) * 100 (9)

(Experimental value)

Comparison result has been shown in Table 6 with prediction error for different responses. In Table 6, ‘Pred’, ‘Expe’ and ‘%’ error are indicating predicted, experimental and percentage error value for each response, respectively. MPPE found for responses Cent, Cexit and HT are 1.8%, 2.2% and 2.8% respectively. All these values are in the range of acceptable limit. It is cleared that all developed models are reliable and acceptable. Now, these models may be used as predicted models [B. Yilbas 1996 & B. Yilbas 2008].

PARAMETRIC ANALYSIS

Improving Circularity at Top (Cent)

Hole circularity is always become an important response in hole features due to thermal energy of laser beam is used in hole formation. Here gas pressure and current are significant parameters for hole circularity at entrance (Cent) from Table 5. Response plot is showing in Figure 3.

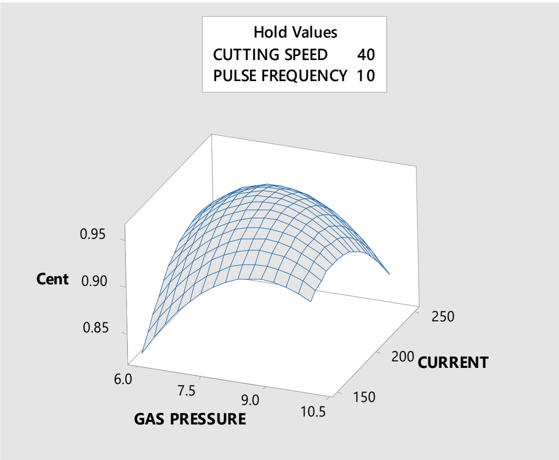

Figure 3. Surface Plot Cent vs Current vs Gas pressure.

From the Figure 3, Cent first increasing with increasing gas pressure and current till mid-range of these parameters. After that Cent is decreasing with increasing gas pressure and current. Maximum Cent is 0.97 (experimental value) at 8kg/cm^2 gas pressure and 200 A current.

While increasing current will increase laser power that will help to melt the metal at top surface of work piece. Simultaneously increased gas pressure will remove molten metal from the surface as earliest possible. But while increasing current above 200A and gas pressure above 8 kg/cm^2. In this condition, material will melt or burn rapidly and melting temperature of around circumference of hole will increase. High gas pressure will remove unwanted material very quickly. So molten material will remove in more quantity that will reduce circularity at top.

Improving Circularity at Bottom (Cexit)

Pulse frequency and current are significant parameters for improving hole circularity at bottom side. Response surface plot has been shown in Figure 4 for the same. In this response surface plot, it can be observed that behavior of current for Cexit is same as Cent. In this case, as increase in current increases circularity till mid-range after that circularity is decreasing with increasing current.

Simultaneously increase in pulse frequency also increases exit circularity till maximum value of pulse frequency. Maximum value of Cexit is 0.96 (experimental value) at current 200 A and pulse frequency 9 Hz. Increase in pulse frequency increases repetition rate of laser beam. So, penetration rate of laser beam will increase. Simultaneously current is increased, then unwanted material will melt in less time and remove quickly from material surface. That will improve hole circularity.

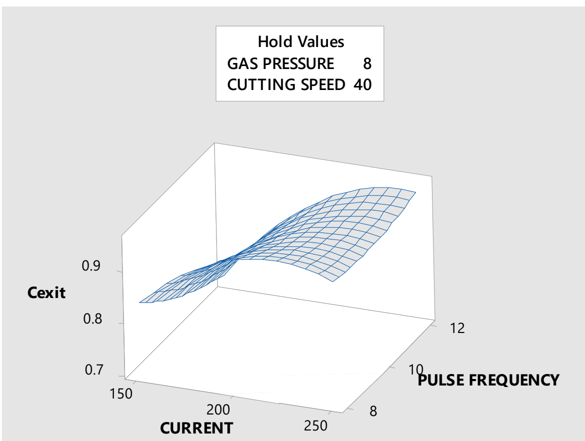

Figure 4. Surface plot Cexit vs Pulse frequency vs Current.

Improving Hole Taper (HT)

Current and CS are significant parameters for hole taper. Converging diverging property of laser beam give taperness during hole making operation. Minimum value of HT will help to give uniform hole diameter (top to bottom), it improves hole feature. Its significant parameters have been discussed earlier. Response surface plot has been shown in Figure 5 for the same. From Figure 5, it can be seen clearly hole taper is decreasing with increasing current. Cutting speed is increased will increase hole taper. Maximum value of current with low cutting speed decreases hole taper. Hole taper 5.32^0 at current is 200 A and cutting speed is 20 mm/min. high current value will increase heat energy and AISI316L is highly thermal conductive material, molten material removes rapidly. Simultaneously less cutting speed and low gas pressure (Table 6) unable to remove melted material from surface and remaining material recast and adhere around the hole. So, hole diameter reduces and difference between hole diameter both sides will be decreased.

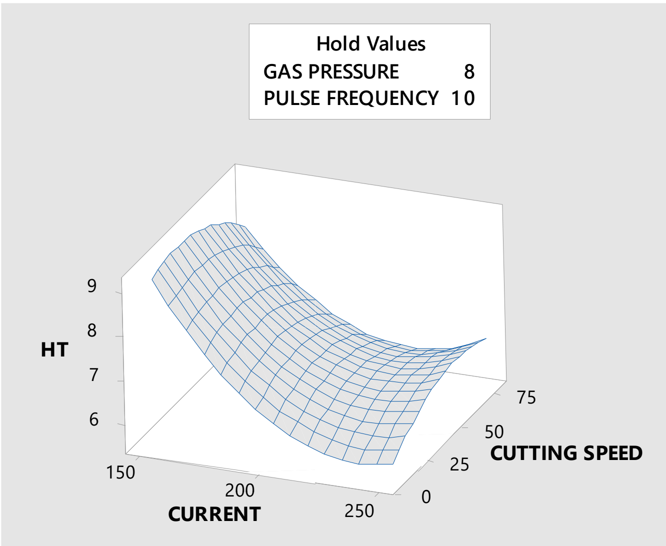

Figure 5. Surface Plot HT vs Cutting Speed vs Current.

CONCLUSION

Design of experiment has been used to prepare an experimental model for modelling of laser drilling of AISI316L sheet for 1 mm hole diameter. RSM and ANOVA techniques have been used to validate all responses and input parameters.

Following out comes have been found in this research work.

a. Regression model for all responses Cent, Cexit and HT are acceptable and trustworthy. P-value for all responses are below 0.05.

b. Mean prediction percentage error for responses Cent, Cexit and HT are 1.8%, 2.2% and 2.8% respectively.

c. Current and gas pressure are found significant process parameters for circularity at top side (Cent). Maximum Cent is 0.97 (experimental value) at 8 kg/cm^2 gas pressure and 200 A current. Current and pulse frequency are found significant process parameters for circularity at bottom side (Cexit). Maximum value of Cexit is 0.96 (experimental value) at current 200 A and pulse frequency 9 Hz.

d. Current and cutting speed are significant parameters for hole taper. Minimum value of hole taper 5.32^0 at current is 200 A and cutting speed is 20 mm/min.

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