Defence Science Journal, Vol. 69, No. 1, January 2019, pp. 37-45, DOI : 10.14429/dsj.69.12879

Particle Swarm Optimisation of Hole Quality Characteristics in Laser Trepan Drilling of Inconel-718

Kedari Lal Dhaker[#] and Arun Kumar Pandey[*]

[#]*Mechanical Engineering Department, Jaypee University of Engineering and Technology, Guna - 473 226, India*
[*]*Department of Mechanical Engineering, Bundelkhand Institute of Engineering and Technology, Jhansi - 284 128, India*
[*]*E-mail: arunpandey76@gmail.com*

ABSTRACT

Inconel-718 is a nickel based super alloy and is extensively in use for working at very high temperature (upto 2000 °C) such as aero engine gas path equipment, nuclear equipment etc. Drilling micro size hole in such material with laser beam has been a proven choice and laser drilling process produces geometrically and dimensionally improved hole. Hole geometrical features can be improved further if laser drilling system operated at optimal input parameter setting. This paper experimentally investigates the behavior of hole geometrical features hole circularity and hole taper in laser trepan drilling of Inconel -718 sheet. Optimal value of laser input parameters for improved hole circularity and reduced hole taper have been suggested with the help of computational intelligence technique particle swarm optimisation. The effect of each laser input parameter on hole quality characteristics are also discussed and demonstrated graphically. Finally the experimental validation of the predicted results has been carried out.

Keywords: Laser trapan drilling; Inconel-718; Circularity; Hole taper; Particle swarm optimisation; Regression model

1. INTRODUCTION

Conventional drilling process like punching and twisting is not able to produces quality and precise holes in high tough and better mechanical properties materials such as Inconel 718. The high toughness and better mechanical properties of materials create high temperature zone around the drilling area and causes the thermal stresses and brittleness in worksheet and cutting tool. Therefore, the conventional drilling process is not suitable for the machining of better mechanical properties material which are being in used for technologically advanced applications like aerospace, nuclear equipment manufacturing, and medical equipment, etc[1]. Laser beam drilling, has been proven to be an efficient drilling process that can compete in terms of cost, quality and easy automation for large scale manufacturing or drilling of material such as nickel based superalloy.

Inconel-718 is a nickel based superalloy and one the most difficult to conventionally drilled alloy, in order to satisfy quality and close dimensions requirement[2]. Inconel-718 is extensively in use for working at very high temperature (upto 2000 °C) such as aero engines and gas path equipment[3]. The Generating thousands of close micro size holes in such equipment and material with laser beam has been a proven choice[4].

Two type of laser drilling process available at commercial level, laser trepan drilling (LTD) and laser percussion drilling (LPD). Laser trepan drilling, is the cutting along the circumference of the hole to be drilled, and laser percussion drilling, is the directly punching of laser beam on the material without any relative motion between work and laser beam[5]. Geometrical quality characteristics such as hole circularity and hole taper of laser trepan drilled hole are better than laser percussion drilled hole[6]. Laser trepan drilling also exhibit some geometrical and metallurgical defects such as poor circularity, tapered hole, barreling, metallurgical defects, recast layer etc[7]. Therefore improving these defects in laser trepanning drilling and getting improved geometry of hole is the major issues for manufacturer. Circularity and hole taper are the severe geometrical defects if components are being used in advanced applications such as gas turbine components, marine components, and automobile parts, etc.

The researchers have studied the laser machining and drilling processes in different ways. Pandey and Dubey[8] improved the laser cut geometry of duralumin sheet by applying the hybrid approach of robust parameter design methodology and Fuzzy logic theory. Similarly Norkey and Dubey[9] have developed mathematical model and did optimisation by genetic algorithm (GA) of heat affected zone (HAZ) in pulse-Nd:YAG laser cutting of duralumin sheet. Chien and Huo[10] have achieved the minimum recast layer thickness in laser trepan drilling by Taguchi based analysis on material Inconel-718. Goyal and Dubey[11] have improved the hole circularity and hole taper in laser trepan drilling of titanium alloy sheet by applying the regression analysis and genetic algorithm. Marimuthu[12], *et al.* have studied the Quasi-CW-fibre laser trepanning drilling of

Received : 14 May 2018, Revised : 25 October 2018
Accepted : 12 December 2018, Online published : 10 January 2019

nickel based alloy and controlled the recast layer, oxide layer, hole surface roughness and suggested the reduced recast layer thickness to 30 µm.

Tamrin[13], *et al.* had achieved lower HAZ in Laser percussion drilling of three different thermoplastics by using grey relational analysis. Hajdarevic and Bijelonja[14] had found the temperature distribution by finite element method (FEM) and experimentally validate the findings. Rajesh[15], *et al.* have developed RSM models for circularity and taper in laser drilling of austenitic stainless steel. Chaudhary[16], *et al.* have developed artificial computational based software tool for simultaneously optimisation of laser cutting quality characteristics and validate the tool with previously published results. Dhaker[17], *et al.* have investigated the laser trepan drilling on Inconel-718 and found the better drilled hole diameter by genetic algorithm.

For manufacturing process modeling and optimisation, many soft computing techniques are being in use such as neural networks (NN), fuzzy systems (FS), perception's, evolutionary computation (EC) which include Evolutionary algorithms, genetic algorithms (GA), ant colony optimisation - ACO), Hybrid (neuro – fuzzy, and Swarm intelligence (Particle swarm optimisation – PSO. Particle swarm optimisation (PSO) algorithm is relatively simple and competitive in term of performance[18]. For single objective optimisation this algorithm has been favored when dealing with many real-world optimisation problems[19]. PSO is easy in implementation and can be applied in continues as well discrete variable problem, PSO is emerging as better suitable for engineering system in term of its efficiency and more effectiveness[20] .

After studying the available research literature on laser drilling, it has been concluded that conventional drilling is being replacing by laser drilling processes for getting improved hole quality. Geometry of laser drilled holes can be improved if laser process parameters are being set at their optimal levels. Laser input parameters such as assist gas pressure, laser current, stand-off distance, trepanning speed and pulse frequency, greatly affect the hole geometry. The authors find very little research available in laser trepan drilling and could not find any research paper on PSO based optimisation of laser trepan drilling process.

Research presented here is an effort to further add to an existing knowledge in laser trepan drilling process and suggest optimal values of laser input parameters for improved hole circularity and reduced hole taper in laser trepan drilling of extensity used Inconel-718 material. The experiments have been performed as per one parameter at time (OPAT) variation. A second order regression model has been developed for hole circularity and hole taper. Optimal result for improved hole circularity and reduced hole taper has been obtained by particle swarm optimisation (PSO) technique. Effects of each input parameter on hole circularity and hole taper have been discussed and demonstrated graphically. Finally the experimental validation of the predicted results has been carried out.

2. EXPERIMENTAL WORK AND MEASUREMENT

2.1 Work Material

In present research, the Inconel-718 sheet of size 140x140x1.4 mm is taken for performing the required experiments. The Inconel-718 sheet is supplied by commercial vender –Randhir metal Pvt. Ltd. (Mumbai).

2.2 Experimental Setup

Laser drilling system consists of three major subsystems.

(a) Laser generation system,
(b) Laser delivery system,
(c) Work holding system

Present experiments are performed on solid state Pulsed Nd:YAG laser of 250W average power. Laser system have been design and developed by at Raja Rammna Center for Advanced Technology Indore, India (RRCAT-Indore). Laser drilling system is shown in Fig. 1 and system specification is given Table 1.

Table 1. Laser drilling system specification

Characteristics	Value
Average power	250 kW
Laser wavelength	1064 nm
Operation mode	Pulsed mode
Pulse width	10 nm
Transmission efficiency	90 %
Focused spot diameter	400 µm

Figure 1. Image of laser trepan drilling system.

2.3 Input Parameters Levels

The important controlling factors, assist gas pressure, laser current, stand–off distance, trepanning speed and pulse frequency have been considered for experiments. These parameters have been decided based on their importance or functional requirements for governing the geometrical quality characteristics.

2.3.1 Assist Gas Pressure

Function of assist gas is to eject the molten metal from drill area immediately after melting otherwise it get re-casted or re-solidify to parent metal and produces the poor quality hole. The pressure of assist gas governs the cooling and ejection of metal properly. Higher pressure creates the force convection cooling and lower pressure may not be sufficient for proper ejection of metal.

2.3.2 Laser Current

The peak power is directly proportional to the lamp current as given by the Eqn. (1). Controlling the laser lamp current directly influences the peak power supplied to work material[21].

$$LaserPeakPower\,(P) = \eta k_0 I^{2/3} \quad (1)$$

where η = conversion efficiency electrical lump in to laser output

k_o = constant for a given flash lamp

I = lamp current

2.3.3 Stand-off Distance

Stand-off distance (SOD) is the distance between nozzle tip to upper surface of work sheet. Changing the SOD changes the focal position of the laser beam. Laser power density is highest at the focal point of beam as focused dia is lowest as this point. If the focal plane is outside the material sheet then poorer melting and geometry will be resulted. Therefore, proper selection of SOD is required for better melting and quality.

2.3.4 Trepanning Speed

Trepanning speed is the relative speed between work sheet and laser delivery nozzle. Higher speed provides less time available for power supply at melting front and lower speed can be cause of uneven or over heating of drilling area.

2.3.5 Pulse Frequency

Laser beam is delivered in pulse mode. Energy supplied to work material depends on the number of beam pulses are being delivered in unit time. High frequency cause the large energy delivery and low frequency cause the poor melting of work sheet.

For finding the range of these input parameters, pilot experiments are performed for getting the through drilled holes. The five levels of input process parameters have been decided based on the observations of pilot experiments and machine capability. The different parameters and theirs values corresponding to the different levels are listed in Table 2.

Table 2. Levels of laser drilling process input parameters

Symbol	Input parameter	L-1	L-2	L-3	L-4	L-5
X_1	Assist gas pressure (bar)	6	7	8	9	10
X_2	Laser current (amp)	220	240	260	280	300
X_3	Stand-off distance (mm)	0.8	1.00	1.25	1.45	1.7
X_4	Trepanning speed (mm/min)	10	20	30	40	50
X_5	Pulse frequency (Hz)	5	10	15	20	25

2.4 Measurements of Hole Diameters

Four diameter d_1, d_2, d_3, and d_4 are measured along the circumference of each drilled hole at interval of 45° angle. The measurements have been performed on tool bit type microscope having least count 0.001 cm and with maximum magnification of 10X. Figure 2 shows the scanned photograph of the specimen after laser drilling.

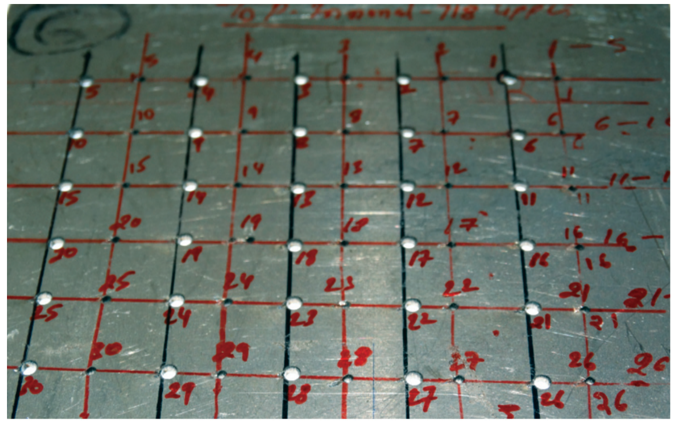

Figure 2. Scanned photograph of the specimen after drilling.

2.5 Calculation of Hole Quality Characteristics

The hole circularity has been defined as in Eqn. (2) and hole taper has been defined in Eqn. (3).

$$C_{ent} = \frac{(d_{\min})_{ent}}{(d_{\max})_{ent}} \quad (2)$$

$$\theta = \tan^{-1}\left(\frac{d_{ent} - d_{exit}}{2t}\right) X \frac{180}{\pi} \quad (3)$$

$$d_{ent} = \frac{(d_1 + d_2 + d_3 + d_4)}{4}$$

$$d_{exit} = \frac{(d_1 + d_2 + d_3 + d_4)}{4}$$

$(d_{min})_{ent}$ = Minimum measured diameters at entrances side

$(d_{max})_{ent}$ = Maximum measured diameters at entrances side

C_{ent} = circularity at entrance side

θ = Hole taper

The value of circularity and hole taper have been calculated for each drilled hole and graphically represented in Fig. 3. The Fig.4 indicates the variation of the measured diameters at entrance and exit during experimentation.

3. MATHEMATICAL MODELING OF QUALITY CHARACTERISTICS

With the help of regression analysis, a mathematical relation can be built between stated input variables and output features.

3.1 Regression Modelling

For better prediction of output parameter, the second order regression model is more suitable over first -order model[22] and general equation of second order regression model is given as Eqn. (4);

$$y = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \sum_{i=1}^{n} \beta_{ii} X^2_i + \sum_{i=1}^{n} \sum_{j=n+1}^{n} \beta_{ij} X_i X_j \quad (4)$$

βs are regression coefficients and value can be found by least square method, X_i (i= 1, 2, 3,- - - n) is value of n different input parameters, y is response parameter. Regression models

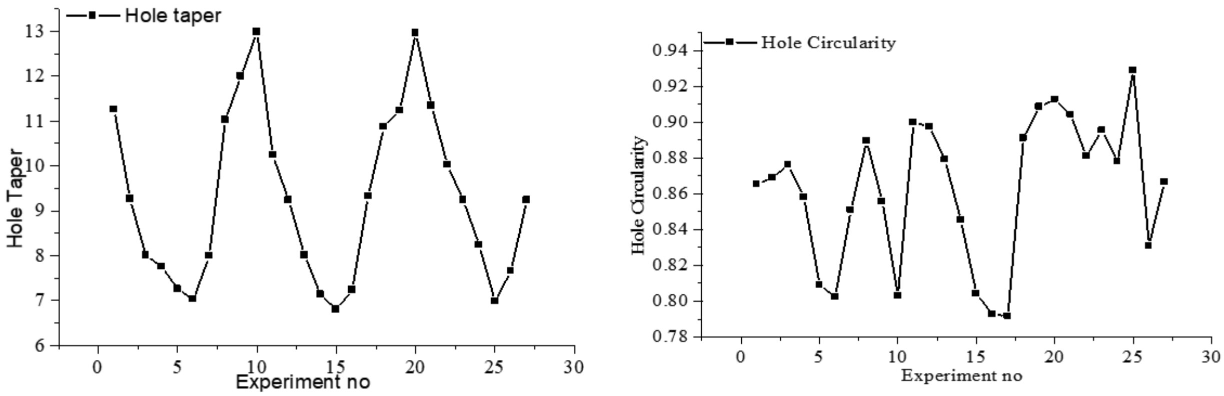

Figure 3. Numerical values of hole circularity and hole taper for each experiment.

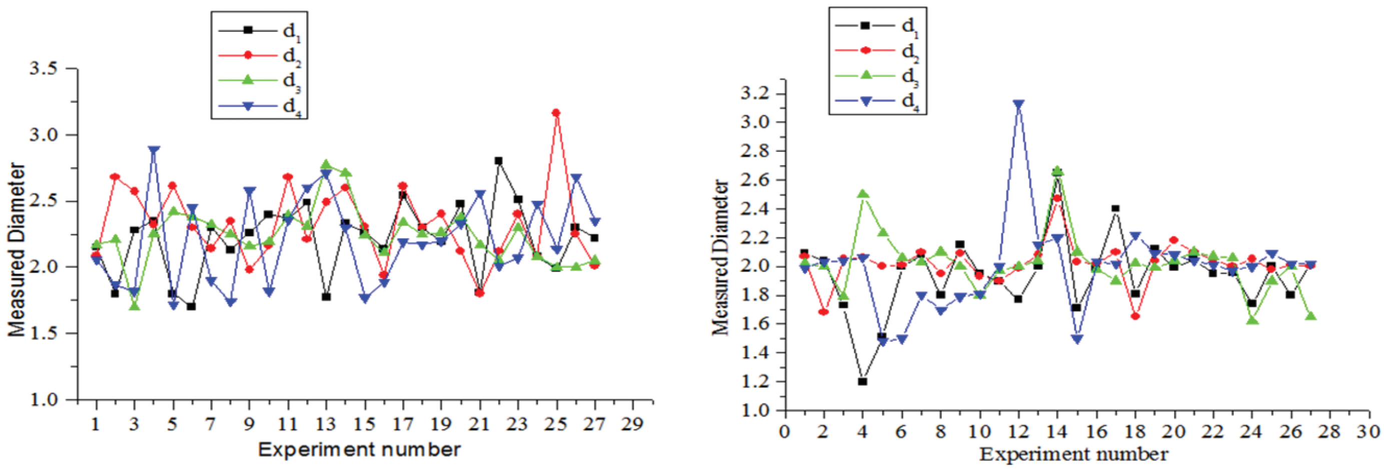

Figure 4. Variation of measured diameters at (a) entrance; (b) exit.

for hole circularity at entrance and hole taper are developed. The MINTAB14 software has been used to find the values of β and p-value of each term in regression models. Insignificant term in the model is removed by using back elimination process for better reliability of developed models. Final developed models for hole circularity and hole taper are Eqns. (5) and (6).

$$\begin{aligned} C_{ent} = {} & 0.502 + 0.0138 * X_1 + 0.00089 * X_2 \\ & + 0.0912 * X_3 - 0.00471 * X_4 + 0.0107 * X_5 \\ & - 0.0197 * X_1 * X1 - 0.000017 * X_2 * X_2 \\ & - 0.0783 * X_3 * X_3 + 0.000086 * X_4 * X_4 \\ & - 0.000440 * X_5 * X_5 + 0.00116 * X_1 * X_2 \end{aligned} \tag{5}$$

$$\begin{aligned} HT = {} & -16.2 + 7.80 * X_1 - 0.108 * X_2 + 2.56 * X_3 \\ & - 0.093 * X_4 - 0.150 * X_5 + 0.228 * X_1 * X_1 \\ & + 0.000908 * X_2 * X_2 - 2.55 * X_3 * X_3 \\ & - 0.00022 * X_4 * X_4 - 0.00144 * X_5 * X_5 \\ & - 0.0379 * X_1 * X_2 \end{aligned} \tag{6}$$

3.2 Model Validation and Adequacy Checking

Validity test has been carried out of developed regression models for that the S-values and coefficients of determination (R^2 and adjusted-R^2 values) are calculated for each model. The R^2 value for C_{ent} and HT models are 97.5 per cent and 84.0 per cent, respectively given in Table 3 which are in acceptable ranges. Hence, the experimental data of C_{ent} and HT are well fitted in the developed models[23].

Analysis of variance has been carried out with the help of Minitab software as shown in Table 3. The p-values of the source of regression in both the models are lower than 0.01 and calculated F-ratios for source of regressions are 52.17, and 7.15 for C_{ent} and HT models respectively. The p-values and calculated F value as given in Table 3 and are well within range for making model significance[22,24-25]. Hence the developed models are significance and adequate for predicting the output response.

4. PARTICLE SWARM OPTIMISATION BASED OPTIMISATION

Particle swarm optimisation technique was introduced by Kennedy and Eberhart[18]. This technique is simple in concept, easy in implementation, and rapid convergence[26]. The PSO algorithm based on the facts that, each elements (birds) have own velocity and direction. Each bird communicates his position and direction to each of other birds; they identify the bird that is in the best location for reaching the destination, each bird, then, speeds up for best personal and best global (group) position in flocks. By doing so, each bird update their position and finds new local position. And this process continues until the flock reaches a desired destination.

PSO is computational economical in term of memory and speed required for computer system[27]. The flowchart of PSO

Table 3. ANOVA results for developed regression models

Response	Source	Degree of freedom	Sum of square	Mean of sum of square	F	P
	Regression	11	0.0409266	0.0037206	52.17	0.000
C_{ent}	Residual	15	0.0010697	0.0000713		
	Total	26	0.0419964			
	Regression	11	79.045	7.186	7.15	0.000
HT	Residual	15	15.072	1.005		
	Total	26	94.117			
Regression parameters for developed models						
	S-Value		**R^2 (%)**		**Adjusted-R^2 (%)**	
Circularity (C_{ent})	0.00844481		97.5		95.6	
Hole taper (HT)	1.00240		84.0		72.3	

algorithm is shown in Fig. 5[28]. The PSO algorithm consists of mainly five parts as follows.

(a) Problem definition
(b) Specifying the PSO parameters
(c) Initialisation of PSO
(d) Main loop of PSO
(e) Result of PSO

If fitness value is minimum value then optimum result obtained, otherwise PSO loop updates the position and velocity of each particle as per Eqns. (7) and (8). This process continues until best fitness value is obtained.

Objective of this research paper as mentioned earlier is to find maximum value of the hole circularity and minimum value of the hole taper in laser trepanned hole. Equation (6) of hole taper and Inverse of Eqn. (5) of hole circularity are separately defined in different M-file of MATLAB2008 software.

The main process parameters of PSO, like population size = 100, maximum iteration = 1000, Velocity inertia coefficient w = 0.025, Random number R_1 = 0.3, Random number R_2 = 0.3, C_1= 1.5 and C_2= 1.5 are taken for better performing PSO and as range suggested in literature available[29-31]. Number of variable in problem are S = 5.

After specifying the parameters, PSO algorithm initialised with randomly takes position value X_i (value of each variable in range taken is this paper). Value of initial particle velocity V_i can be randomly taken between 0 to 1.

Main loop of PSO start after initialisation, by using three parameters, current position X_i, personal best position P_i, and globally best position P_g. Each particle updates its velocity V_i to reach up the best particle g (solution). With the new velocity, each particle updates its position X_i as represented through Eqns. (7) and (8), respectively[27].

$$V_{inew} = wV_i + C_1R_1\,(P_i - X_i) + C_2R_2\left(P_g - X_i\right) \tag{7}$$

$$X_{inew} = X_i + V_{inew} \tag{8}$$

After defining the objective functions and specifying the PSO parameters, the developed MATLAB program have been executed and by reaching the termination criteria, the optimal value of input variables and optimal value (minimum) of inverse of circularity function and minimum value of hole taper function have been found. By taking inverse of PSO results minimum optimal value (1.03353) of 1/ C_{ent} gives the desired maximum values of hole circularity (C_{ent}). The optimal results obtained by the proposed methodology are given in Table 4. The optimal value suggested by PSO are better than all the calculated value of circularity and hole taper in experiments. The PSO resulted minimum value of inverse of circularity function and minimum of hole taper function are as shown in Fig. 6.

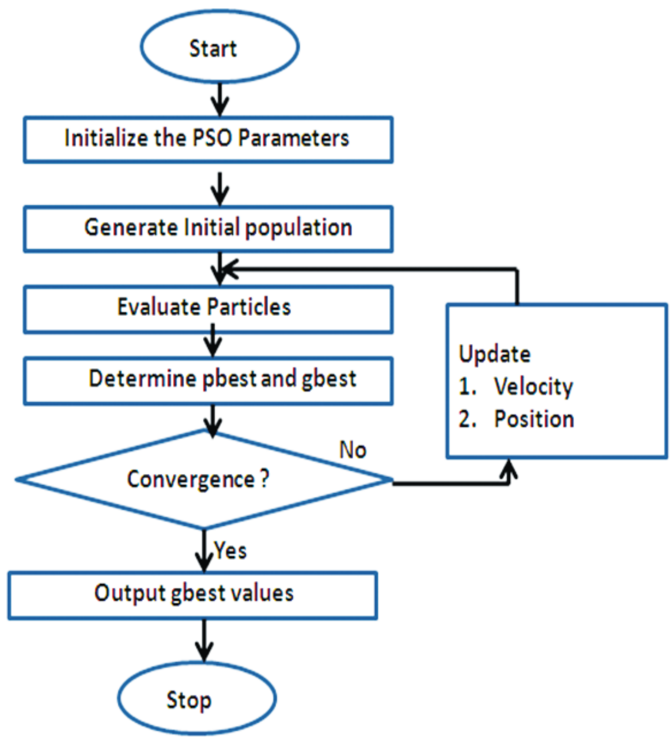

Figure 5 Flow chart of PSO algorithm[28].

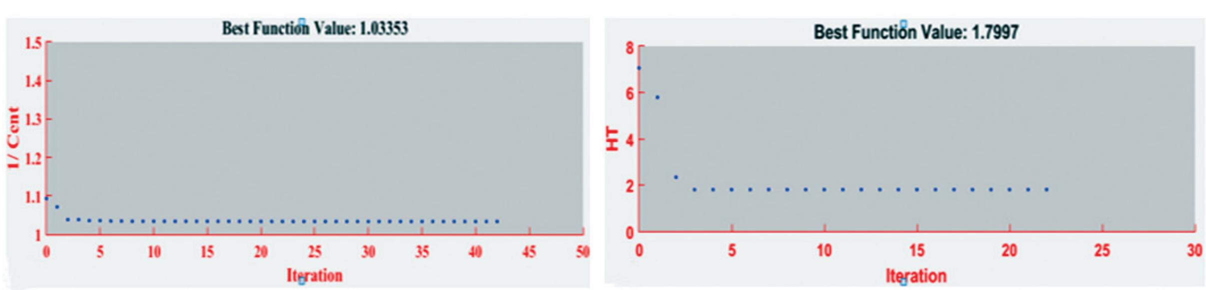

Figure 6. PSO results of minimum value of 1/ C_{ent} function and HT function.

5. RESULT DISCUSSION

5.1 Effect of Assist Gas Pressure and Laser Current on Quality Characteristics

The Fig. 7 shows the effect of assist gas pressure and laser current on the hole circularity and hole taper. By increasing the assist gas pressure, the hole circularity increases upto 8 bar after that it starts decreasing i.e. better circular holes may be created up to 8. Increasing the gas pressure up to 8 bar is responsible for the enhanced force available to eject the melted material and proper ejection of molten metal, minimizes the difference in diameters along the circumference of drilled hole. Due to that the circularity is increasing upto 8 bar. However, it is noted that if gas pressure is more than the required for proper ejection of molten metal, causes the force convection heat loss and rapid cooling of molten metal[10]. This resulting the widen the differences between diameters along the hole circumferences of drilled hole and hence reducing circularity by increasing the assist gas pressure after certain limit i.e. after 8 bar.

The molten material ejected from entrance side may recast at exit side of hole because of forced convection cooling of molten metal at higher gas pressure. Increasing mean entrance diameter and decreasing mean diameter by recasting at exit side, widen the difference between mean entrance and mean exit diameter. Hence increasing gas pressure, increases the hole taper.

As indicated in Fig. 7, by increasing the laser current, increase in the hole circularity has been observed at higher gas pressure but at lower assist gas pressure, no significant increment in circularity have been observed. At laser current 260 amp, combing with large gas pressure, resulting proper melting and ejection of work metal gives better circularity. The excess gas pressure after 8 bar promotes the forced convective cooling of molten metal and form the recast layer, which generates the poor circularity.

Hole taper increases with the increase in gas pressure because at the entrance side i.e. at the top surface of the specimen the molten material is easily ejected out from the cutting zone due to high gas pressure thereby offering more projected area for further melting of the material. However, at the bottom surface, the removal of the material is not proper, as such this leads to the solidification of molten material in the vicinity of the cutting zone. Thus, the drilled hole at the bottom surface is smaller in size as compared to the hole at the top surface. The hole taper is directly proportional to the difference in the top and bottom diameters. With the increasing gas pressure, the difference between these two diameters is enhanced thereby resulting in higher hole taper.

5.2 Effect of Pulse Frequency and Stand-off Distance on Quality Characteristics

By increasing pulse frequency, the hole circularity

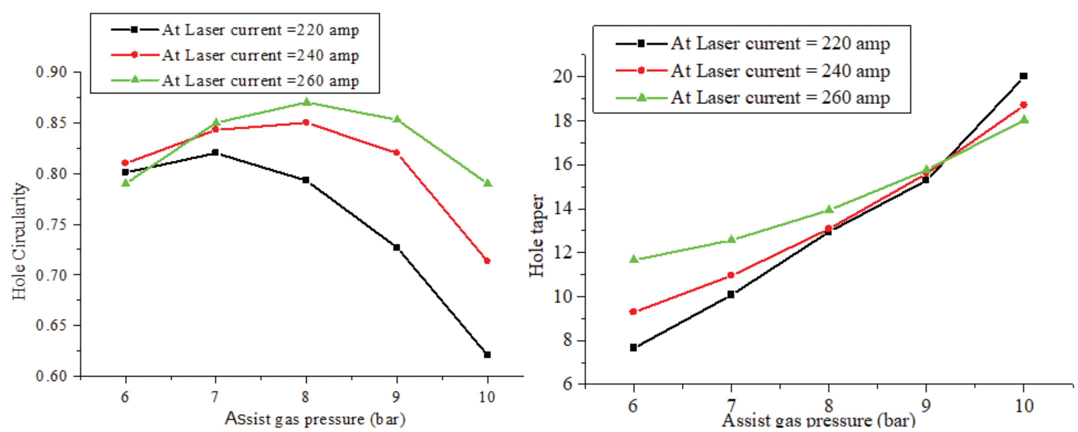

Figure 7. Effect of assist gas pressure and laser current on circularity and hole taper.

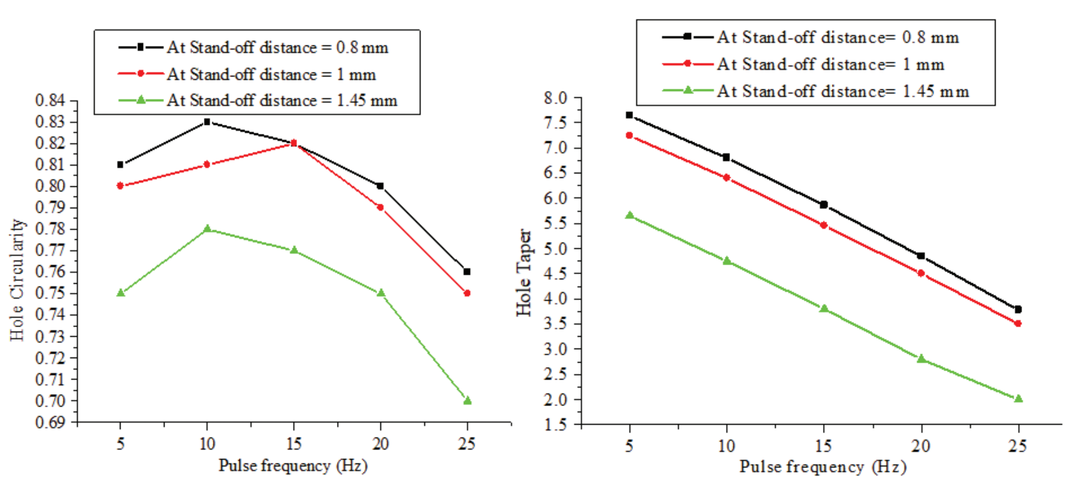

Figure 8. Effect of pulse frequency and SOD on circularity and hole taper.

decreases after 10 Hz in range taken. The hold value are Assist gas pressure = 6 bar, Laser current = 220 amp and Trepanning speed = 10 mm/min for the analysis. As shown in Fig. 8, At higher pulse frequency, laser energy is delivered repeatedly in short time, and molten material removal process may not finished before next pulse of energy delivered to drill area. That causes the excess heat reaches the material and increasing variation in diameters along the drill hole circumference is the reason for decreasing circularity.

Increasing SOD creates the positive focal plane position (plane at which laser beam is focused) in the sense that focal position is above the work surface. At positive focal position, work material receive less energy due to laser beam energy density is highest at focal plane compare to other plane[32]. Uneven melting of material produces variations in hole diameters along the drilled hole circumference. Therefore, the poor circularity has been observed. At higher pulse frequency combining with higher SOD, larger energy reaches to bottom surfaces, which narrowed the difference between mean entrance diameter and exit diameter. Hence reduces the hole taper.

5.3 Effect of Trepanning Speed and Pulse Frequency on Quality Characteristics

Decreasing pattern of circularity with increasing trepanning speed up to 30 mm/min is indicated in Fig. 9, there after increasing pattern has been observed with increasing trepanning speed. The hold values used for the analysis are Assist gas pressure = 6 bar, Laser current = 220 amp and SOD = 0.8 mm. At lower trepan speed, sufficient time is available for proper ejection of molten metal, and heat is restricted locally due to poor thermal conductivity of material. The molten material remains molten for relatively longer time and being ejected properly, therefore, the formation of recast layer is restricted. These phenomena are responsible for the better hole circularity at lower trepanning speed. However, by increasing the trepanning speed after 30 mm/min, restricts the overheating of material due to less time available for heating. The less time available also restrict the uneven heating and melting of material, and proper heating, melting and ejection of material make reducing variation in diameter measured along circumference. The reducing variation in diameter is the reason for increasing circularity.

At the higher speed combined with high pulse frequency, larger energy supplied for shorter period of time. Hence, the overheating and recast layer formation restricted at both side of hole and reduced hole taper can be obtained. At lower pulse frequency, less energy delivered to work material. At low energy, the random heating and melting makes poor circular hole. Similarly, at lower pulse frequency, the top side of hole melts more as compare to bottom side due less energy available and poor thermal conductivity of material. The large melting at top side widen the difference between mean entrance diameter and mean exit diameter. Widen difference in diameter is the reason for increasing hole taper with decreasing pulse frequency.

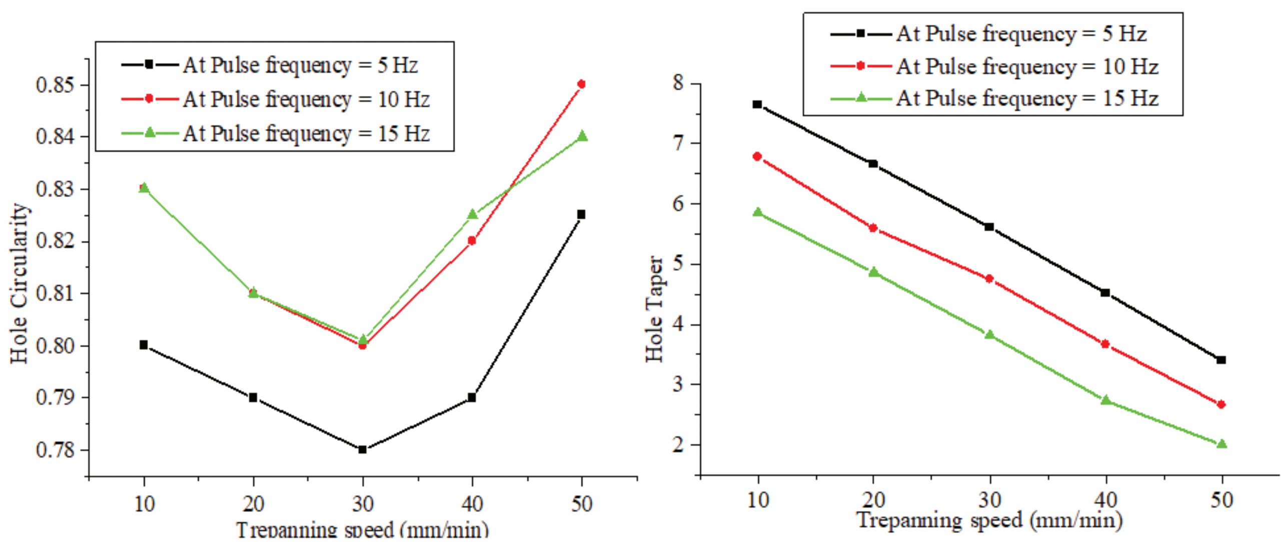

Figure 9. Effect of trepanning speed and pulse frequency on circularity and hole taper.

Table 4 Confirmation results

Response	Input parameter setting	Predicted values	Experimental values	Best value found during 27 experiments	Improvement (%)
Hole circularity	X_1= 9.20, X_2= 300, X_3= 0.80, X_4= 50, X_5= 12.20	0.97	0.98	0.93	5.37
Hole taper	X_1 = 6, X_2 = 220, X_3 = 0.8, X_4 = 10, X_5 = 5	1.80	2.85	6.65	57.14

5.4 Optimum Results

The optimal value of hole circularity has been found is 0.97, at level of assist gas pressure 9.20 bar, laser current 300 amp, SOD 0.8 mm, trepanning speed 50 mm/min and pulse frequency 12.20 Hz. For the experimental validation, the confirmation experiments have been conducted at optimum parameter setting. The comparison results are given in Table 4. From the Table 4, it is clear that the optimum experimental results show that an improvement of 5.37 per cent has been found in circularity as compared to the maximum value of hole circularity obtained during the experiments.

High laser current (300 amp) is responsible for high energy delivered to work material, but with combining with high trepanning speed (50 mm/min), high assist gas pressure (9.20), Lower SOD and medium pulse frequency provides the opportunity for proper heating and melting of work material. The higher Assist gas pressure removes all the melted material immediately from drilling area and high trepanning speed provides the shorter time available for laser beam interaction with work material, which makes better circular hole with improved circularity (0.97).

Similarly optimal value of Hole taper (HT) has been found is 1.8° at level of assist gas pressure 6 bar, laser current 220 amp, SOD 0.8 mm, trepanning speed 10 mm/min. and pulse frequency 5 Hz. For the experimental validation, the confirmation experiments have been conducted at optimum parameter setting. From the Table 4, it is clear that the optimum experimental results show that an improvement of 57.14 per cent has been found in hole taper as compared to minimum values obtained during the experimentation for the research i.e. out of 27 experiments.

Combing effects of low laser current (220 amp) and low frequency (5 Hz) is lower energy delivered to work material and due poor thermal conductivity of material, heat given to material confined in narrowed drilling area. Lower laser current with combination of low assist gas pressure (6 bar) and lower trepanning speed (10 mm/min.) limits the melting and removal of material from drilling area. Restricted melting and poor removal of molten metal generates the smaller diameter hole at entrance side. Lower entrance mean diameter narrows the difference between mean entrance diameter and mean exit diameter, which ultimately resulting in reduced hole taper (1.8°).

6. CONCLUSIONS

Laser trepanning drilling on material Inconel-718 has been performed for getting improved circularity and reduced hole taper. Following are the main finding of this research.

(a) Experiments of laser trepan drilling are performed on Inconel-718 extensively used in advanced mechanical component manufacturing.
(b) Reliable and adequate multi–regression mathematical models of hole circularity and hole taper are developed for predicting the hole quality characteristics.
(c) Computational intelligence technique, particle swarm optimisation (PSO) has been successfully applied for finding the optimal laser input parameters for improved circularity and reduced hole taper.
(d) Maximum circularity has been obtained at higher gas pressure, highest laser current, lowest SOD, highest trepan speed and medium pulse frequency.
(e) Reduced hole taper has been found at lower assist gas pressure, lower laser current, lower trepanning speed and low pulse frequency.
(f) The confirmation results show an improvement of 5.37 per cent and 57.14 per cent in hole circularity and hole taper at optimum parameter settings.

REFERENCES

1. Jain, V.K. Advanced machining processes. Allied publisher pvt., New Delhi, 2005. 2 -8 p.
2. Chyryssouris, G. Laser machining-Theory and practice. Springer, New york, 2005. 3 p.
3. Ezugwu, E.O.; Wang, Z.M. & Machado, A.R. The machinability of nickel based alloys - A review. *J. Mater. Proces. Technol.*, 1999, **86**, 1–16. doi: 10.1016/S0924-0136(98)00314-8
4. Yeo, C.Y.; Tam, Jana, S.C.S. & Lau, M.W.S. A technical review of the laser drilling of aerospace materials. *J. Mater. Proces. Technol.*, 1994, **42**, 15–49. doi: 10.1016/0924-0136(94)90073-6
5. Dubey, A.K. & Yadava, V. Laser beam machining – A review. *Int. J. Mach. Tools Manufacture*, 2008, **48**, 609-628. doi: 10.1016/j.ijmachtools.2007.10.017
6. Kumar, S.; Dubey, A.K. & Pandey, A.K. Computer-aided genetic algorithm based multi-opbjective optimization of laser trapan drilling. *Int. J. Pricision Eng. Manufacuring*, 2013, **14**, 1119-1125. doi: 10.1007/s12541-013-0152-5.
7. Choudhury, I. A.; Chong, W.C. & Vahid, G. Hole qualities in laser trepanning of polymeric materials. *Optics Lasers Eng.*, 2012 , **50**, 1297–1305. doi: 10.1016/j.optlaseng.2012.02.017
8. Pandey, A.K. & Dubey, A.K. Taguchi based fuzzy logic optimization of multiple quality characteristics in laser cutting of Duralumin sheet. *Optics Lasers Eng.*, 2012, **50** 328–335. doi: 10.1016/j.optlaseng.2011.11.005
9. Norkey, G.; Dubey, A.K. & Agarwal, S. Artficial intellegenec based modeling and optimization of heat affcted zone in Nd:YAG laser cutting of duralumin sheet. *J. Intel. Fuzzy Sys.*, 2014, **27**(3), 1545-1555. doi: 10.3233/IFS-141121
10. Chien, W.T. & Hou, S.C. Investigating the recast layer formed during the laser trepan drilling of Inconel 718 using the Taguchi method. *Int. J. Adv. Manufacturing Technol.*, 2007, **33,** 308–316. doi: 10.1007/s00170-006-0454-1
11. Goyal, R. & Dubey, A.K. Modeling and optimization of geometrical characteristics in laser trepan drilling of titanium alloy. *J. Mech. Sci. Technol.*, 2016, **30**(3) , 1281-1293. doi: 10.1007/s12206-016-0233-3
12. Marimuthu, S.; Antar, M.; Dunleavey, J.; Chantzis, D.; Darlington, W. & Hayward, P. An experimental study on quasi-CW fibre laser drilling of nickel superalloy. *Optics*

Laser Technol., 2017, **94**, 119–127.
doi: 10.1016/j.optlastec.2017.03.021

13. Tamrin, K.F.; Nukman, Y.; Choudhury, I.A. & Shirley, S. Multiple-objective optimization in precision laser cutting of different thermoplastics. *Optics Lasers Eng.*, 2015, **67**, 57–65.
doi: 10.1016/j.optlaseng.2014.11.001
14. Hajdarevic, D.B. & Bijelonja, I. Experimental and numerical investigation of temperature distribution and hole geometry during laser drilling process. *Procedia Engineering*, 2015, **100**, 384 – 393.
doi: 10.1016/j.optlaseng.2014.11.001
15. Rajesh, P.; Nagaraju, U.; Harinath Gowd, G. & Vishnu Vardhan, T. Experimental and parametric studies of Nd:YAG laser drilling on austenitic stainless steel. *Int. J. Adv. Manufacturing Technol.*, 2017, **93**, 65–71.
doi: 10.1007/s00170-015-7639-4
16. Chaudhary, A.K.; Pandey, A.K. & Dubey, A.K. Computer aided taguchi-fuzzymulti-optimization of laser cutting process. *J. Intel. Fuzzy Sys*., 2014, **26**(2), 801-810. doi: 10.3233/IFS-130770
17. Dhaker, K.L.; Pandey, A.K. & Upadhayay, B.N. Experimental investigation of hole diameter in laser trepan drilling of Inconel718 sheet. *Mater. Today: Proce.,* 2017, **4** , 7599–7608.
doi: 10.1016/j.matpr.2017.07.093
18. Kennedy, J. & Eberhart, R.C. Particle swarm optimization. *In* Proceedings of IEEE International Conference on Neural Networks 2005: Piscataway, IEEE Service Center NJ, 2005, **5**, 1942–1948
19. Reyes-Sierra, M. & Coello, C. Multi-objective particle swarm optimizers: A Survey of the State-of-the-Art. *Int. J. Comput. Intel. Res.*, 2006, **2**(3) 287–308.
20. Adams II, Thomas A. & Seider, Warren D. Practical optimization of complex chemical processes with tight constraints. *Comput. Chem. Eng.,* 2008, **32**, 2099-2112.
doi: 10.1016/j.compchemeng.2008.02.007
21. Joshi, P. & Shrma, A. Simultaneous optimization of kerf taper and heat affected zone in Nd-YAG laser cutting of Al 6061-T6 sheet using hybrid approach of grey relational analysis and fuzzy logic. *Precision Engineering*, 2018, **54**, 302-313.
doi: 10.1016/j.precisioneng.2018.06.007
22. Montgomery, D.C. Design and analysis of experiments. wiley India, New Delhi, 2009. 389 p.
23. Phadke, M.S. Quality engineering using robust design. Prentice-hall, NJ, 1989. 51 p.
24. Gillett, B.E. Introduction to operation research –A computer–oriented algorithmic approach. Tata McGraw-Hill, New Delhi, 2008.
25. Pandey, A.K. & Dubey, A.K. Simultaneous optimization of multiple quality characteristics in laser cutting of titanium alloy sheet. *Optics Laser Technol.*, 2012, **44**, 1858–1865. doi: 10.1016/j.optlastec.2012.01.019
26. Mohanty, C.P.; Mahapatra, S.S. & Singh, M.R. A particle swarm approach for multi-objective optimization of electrical discharge machining process. *J. Intel. Manufacturing,* 2016, **27**, 1171–1190.
doi: 10.1007/s10845-014-0942-3
27. Yusup, N.; Zain, A.M. & Mohd Hashim, S.Z. Overview of PSO for optimising process parameters of machining. *Procedia Engineering*, 2012, **29**, 914–923.
doi: 10.1016/j.proeng.2012.01.064
28. Rao, R.V. Advanced modeling and optimisation of manufacturing process. Springer, London, 2011. 37 p.
29. Garg, H. & Sharma, S.P. Multi-objective reliability-redundancy allocation problem using particle swarm optimization. *Comp. Indust. Eng.*, 2013, **64**, 247–255.
doi: 10.1016/j.cie.2012.09.015
30. Garg, S.; Patra, K. & Pal, S.K. Particle swarm optimization of a neural network model in a machining process. *Indian Academy Sci.*, 2014, **39**(3), 533–548.
doi: 10.1007/s12046-014-0244-7
31. Das, S.; Abraham, A. & Konar, A. Particle swarm optimization and differential evolution algorithms: Technical analysis, applications and hybridization perspectives. *Stud. Comp. Intel.*, 2008, **116**, 1–38.
doi: 10.1007/978-3-540-78297-1_1
32. Ghoreishi, M.; Low, D.K.Y. & Li, L. Compartive statistical analysis of hole taper and circularity in laser percussion drilling. *Int. J. Mach. Tool Manufacuring*, 2002, **42**, 985-995. doi: 10.1016/S0890-6955(02)00038-X

ACKNOWLEDGEMENT

We are thanks full to Dr B.N. Upadhayay, Senior scientist at Government of India's Raja Ramanna Centre for Advanced Technology (RRCAT)-Indore, India. Dr Upadhayay has supported us by allowing for conduction of experiments at their advanced laser cutting facility for this research purpose.

CONTRIBUTORS

Mr Kedari Lal Dhakar, has completed BE (Mechanical) from MITS-Gwalior (MP) and ME (Production Engineering) from Delhi College of Engineering, Delhi. Presently pursuing his PhD from Bundelkhand Institute of Engineering and Technology, Jhansi. Currently working as Assistant Professor in the Department of Mechanical Engineering at Jaypee University of Engineering & Technology, Guna.
He has conducted the experiments, measured the quality characteristics and analysed the experimental data by proposed methodology. He has also contributed in writing the research paper.

Dr Arun Kumar Pandey received his BTech (Mechanical Engineering) from Mahatma Gandhi Gramoday Vishwavidyalay Chitrakoot, Satna and MTech (Production) from M.I.T.S. Gwalior. He received his PhD from M.N.N.I.T. Allahabad. Presently working as Associate Professor at Bundelkhand Institute of Engineering and Technology, Jhansi. His research area is Advanced machining processes, Laser beam machining, application of artificial intelligence based tools for modeling and optimisation, application of design of experiment methods, laser cutting of difficult-to-laser cut materials, electrical discharge machining.
He has supervised to conduct the research and analysed the experimental data. He has also supervised the result and analysis and writing the research paper. He has also revised the manuscript based on the reviewers comments.