Parameter Optimization of CO_2 Laser Drilling for Different Features

Siddhant R. Gade[1], Dr. K. H. Inamdar[2]

[1]P.G. student College of Engineering, Sangli, Maharashtra - 416415

[2]Professor, Department of Mechanical Engineering, Walchand College of Engineering, Sangli, Maharashtra – 416415

Abstract: ***Paper mainly enlightens the use of Laser for drilling using optimization of different input variables such as laser power, scanning speed, gas pressure. The quality of hole drilled is measured and validated by response variables such as hole taper, surface roughness .To judge the quality of hole, different parameters are playing important role. Nowadays laser drilling is used to minimize the working time with preferable cost.***

Keywords: Laser, quality, hole, variables

1. Introduction

The basic concept of laser is given by an American scientist Charles Hard Townes and two Soviet scientists are Alexander Mikhailovich Prokhorov and Nikolai Gennediyevich Basov. Now day's laser machining is widely used for different applications like drilling, cutting, forming etc.[1].

Manufacturing is the transformation of materials into goods for the satisfaction of human needs [2]. In the engineering field it is found to be, a machining is an important area. It has been noticed that, to fulfill the today's challenges, there is need to use advanced technologies in production process. Laser machining is the advanced machining process belongs to family of machining and laser based machine tools can be considered as an advanced machining process. Now days laser based systems can refer non-conventional process.

If the component is going to be used in a precise device, variation among holes such as taper, roundness etc. must be within certain limits. Laser based machining process find the application in various industries because of their precision, low cost, localized processing, high speed of operation, less material loss and less fatigue to operator. Laser Drilling is the one of application where heat of laser beam is used to melt and evaporate the required area of material. For industry application like in aerospace, power, electronic, and sheet metal forming Laser drilling has become an integral part.

Laser drilling is an important process of industry, with which laser pulses are used to drill holes in different material's ranging from metal to non-metal with varying shapes and thickness. There are some characteristics of laser drilling, low heat input into material, accuracy, consistency, easy to automate and the possible hole diameter with laser drilling is between 0.005 to 1.5mm with aspect ratio (depth/diameter) less than 1 to above 50. Vaporization and melt ejection are the two mechanisms through which material removed from the workpiece during drilling [4]. During evaporation process, the evaporating front detaches from the liquid surface produces a recoil pressure across the vapor–liquid interface. The recoil pressure increases as the evaporation of the surface progresses, influencing the evaporation rate.

2. Literature Review

Literature review is done to gain knowledge about laser drilling process. Before performing any experiments, literature review is done to get some overview of process parameters and their effects. One of the major challenges that appear during laser drilling is taper and roughness. Following literature survey is carried out.

Drilling of materials like stainless steel and titanium alloys is difficult due to work hardening and rubbing of tools against the hardened zone causing rapid tool wear (Yeo et al. [7]; Tansel et al. [8]). Laser drilling is an alternative way for micro-drilling. Since there is no contact between tool and the work materials, the problem of chatter and vibration during machining can be eliminated (Chryssolouris et al. [9]). The standard lasers used for the laser machining process are ruby laser, Nd:YAG (Neodymium Yttrium Aluminum Garnet) and carbon dioxide (CO_2) gas.

2.1. Geometry of Hole

In manufacturing, circularity of hole at exit and entry are important attributes as well as taper of hole which greatly influence the quality of a drilled hole.

G.Ng et al. [10] investigated the laser percussion drilling on EN3 MS of 2mm thickness. They investigated the drilling process on the basis of repeatability characteristic of produced drilled holes for same fixed parameters. They drilled Thirty five holes for 19 set of parameters thus a total of 665 holes were drilled. Lastly circularity of drilled holes ranges from 0.94 to 0.87 they found and is correlated with repeatability. After analysis higher peak power, and shorter pulse width gives better hole geometry repeatability they concluded. Also Melt ejection and spatter formation have been found to contribute to the poor repeatability of the process.

Bharatish et al. [11] represents the work on CO_2 laser drilling of alumina ceramics. They used orthogonal array experimentation and response surface methodology to find out effect of laser parameters on the quality of drilled holes such as Circularity of drilled hole at the entry and exit, heat affected zone and taper in alumina ceramics. Finally they concluded that, both entrance and exit circularities were significantly influenced by hole diameter and laser power, heat affected zone was influenced by frequency and Taper was also significantly influenced by laser power.

Hussein et al. [12] did the Laser Hole Drilling of Stainless Steel 321H and Steel 33 using 3D CO_2 Laser CNC Machine. Firstly they carried out simulation work on COMSOL 3.5A software, for this they took two cases with or without use of assists gases through nozzle to obtain optimum result for temperature distribution. After this they plotted the graph for same two cases, one is between power and diameter of hole, second plot between exposure time and power and lastly they analyses the result. Then they carried out two experimental works with or without assists gases and analyses the result. They found that, as power increases hole diameter increases and quality of hole is increase when assist gas is used. Lastly they compare the experimental with simulated work.

Pantsar et al. [13] uses two frequency triplicated Nd:YV04 lasers, delivering pulses of width 9 to 12 ps and 12 and 9 to 28 ns were used to form grooves and drill holes in silicon wafers. In this study optical 3D profiling system were used to measure groove depth and geometry. Scanning Electron microscope was used to characterize the drilled holes. They found that pulse energy and repetition rate influences the material removal rate (MRR), when nanosecond beam was used. Also the groove width and depth varied with picoseconds laser beam but volumetric MRR remained constant. Finally by measurement, nanosecond pulses induces not only thermal stresses but damages the hole geometry they concluded.

2.2. Optimization Techniques

Design of experiment (DoE) approach has been extensively used by the researchers to systematically analyze the effect of process parameters on performance output with less number of experimental runs.

Bandyopadhyay et al. [14] did the laser drilling experiment on IN718 and Ti-6Al-4V sheets with the use of Taguchi design of experiments technique to study the effects of the laser process variables on the quality of the drilled holes and ascertain optimum processing conditions. Taweel et al. [15] have proposed a Taguchi method for laser drilling of Kevlar-49 using CO_2 laser. Implementation of Taguchi method helps to systematically analyze the effect of each parameter on quality of laser drilled hole such as taper, kerf width and dross height.

However, the DoE approaches can optimize a single response. When multiple responses need to be optimized simultaneously, the approaches break down. Therefore, a large number of techniques have been suggested for multi-response optimization by combining desirability function approach and grey relation analysis along with DoE suggested by Tosun [16]. S. Nagesh et al. [17] presents the influence of nanofillers on the CO_2 laser drilling of vinylester/glass based on L_9 Orthogonal Array Experiments and Grey Relational Analysis. The Grey–Taguchi method for laser power, cutting speed, air pressure and nano filler content were used to optimize the multiple responses such as Damage Width, Surface Damage Width and taper Angle were optimized using grey relational analysis. Finally they concluded that, based on ANOVA for Grey Relational Grades, nickel nanopowder contributed to the quality of holes to the extent of 65.73%. But the contributions of carbon black and C-15A were 2.9% and 16.28% respectively. Thus, nickel nanopowder effectively improved the quality of laser drilled holes because of its superior thermal properties.

Choudhury et al. [18] did the laser trepan drilling on Acrylonitrile butadiene styrene (ABS) and Polyethylene methacrylate (PMMA) polymer material. Polymeric material having 5mm thickness with laser power, assist gas pressure, cutting speed and standoff distance were four input parameters chosen for different 2mm, 4mm and 6mm diameter of hole. L_9 OA for different 4 factors and 3 levels for each factor were used to perform experiment. From ANOVA analysis, they found that the optimum levels of 4 process variables were different for different hole size and material. Also they found that for ABS polymer circularity of hole at entrance more than that of exit while for PMMA it was opposite

3. Experiment setup

CO_2 laser drilling machine of Yawei HLB-1530 serieswas used for performing the experiments. This machine is available at Power Control Electro Systems Private Limited, Kupwad M.I.D.C, Sangli- 416436. This machine includes an interlocked enclosure that surrounds the drilling area also protects the operator from gantry movement. The enclosure also helps to contain fumes for better dust collection and ensures a cleaner shop environment. Fig. 4.1 shows the head of laser drilling machine.

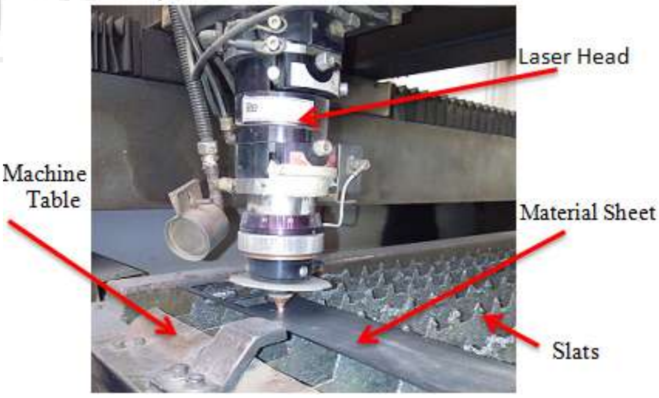

Figure 1: Laser Drilling Head

3.1. Material Selection and Input Parameters Level

Material selected for dissertation work is as per the application of CO_2 laser drilling process, this process is widely used in electrical, aerospace and automobile industries for drilling holes. These industries make extensive use of CO_2 lasers with powers up to several kilowatts.

(a) Chemical Composition of Material

Chemical composition of material of Spring Steel is as shown in Table 4.2.

Table 3.1: Chemical Composition of Spring Steel (C65)

Element	C	Mn	Si	S
Percent (%)	0.60-0.69	0.6-0.90	0.35 max	0.35 max

(b) Properties

- These steels are generally low-alloy Manganese, medium-carbon steel or high-carbon steel with very high yield strength.
- This allows objects made of spring steel to return to their original shape despite significant deflection or twisting

(c) Applications

- Spring Steel nozzles are generally laser drilled for different nozzle operations.

Figure 2: Spring Steel Nozzle

- General piano wire (also known as music wire) such as ASTM A228 (0.80–0.95% carbon), spring clamps, antennas, springs, and vehicle coil springs, leaf springs.
- Spring steel is also commonly used in the manufacture of metal swords both historically and for stage combat due to its resistance to bending, snapping or shattering
- Tubular spring steel is used in the landing gear of some small aircraft due to its ability to absorb the impact of landing
- Spring steel is one of the most popular materials used in the fabrication of lockpick due to its pliability and resilience
- Spring Steel used in the manufacture of springs, prominently in automotive and industrial suspension applications.
- For industry application like in aerospace, power, electronic, and sheet metal forming.

4. Experimentation and Analysis

Based on the literature review, parameters and their levels selected for trial experimentation are as shown in Table 4.3. Experiments were performed on CO_2 laser drilling machine Yawei HLB-1530 series and for programming CNC-CAD 10.59 software was used to perform drilling operations on laser machine. Trial experiments were taken on spring steel of 4mm thickness and laser beam having 127mm focal length and various beam diameters. For all experiments there was a sensor which keeps 1mm constant distance between sheet and nozzle of laser head.

Before doing experiments, firstly it is required to draw a profile having required shape in AutoCAD software. Then this drawing needs to feed into CNC-CAD 10.591 software where programming is done for particular profile to get the path for laser beam. In programming input parameters such as laser power, scanning speed and gas pressure were defined. After this, the program of CNC-CAD 10.591 was required to feed into Autonest 10.591 software that operates the laser machine. According to input parameters, operator of Autonest software can set the size of sheet and choose the number of profiles that are going to make.

Figure 3: Laser Machining

4.1 Selection of process parameters and their level

As already discussed in chapter number 3, it is possible to have number of process parameters can be changed during experimentation. But according to specification of laser system, need to choose parameters. Same laser system with available specification used for trial experiment was also used for final experiment on Spring Steel.

It is more important to choose process parameters and their level for getting better result. The most affecting process parameters of laser system and their level selected for final experiment were based on literature review and from trial experiment .

4.2. Selection of Orthogonal Array for Final Experiment

Depending upon the levels of a factor or process parameter, a 2 or a 3 level OA can be selected. If some factors are of two-level and some of them are three-level, then whichever is predominant factor should indicate which kind of OA is selected. Once the decision is made about the right OA, then the number of trials for that array must provide an adequate total number of DF, and when required DF fall between the two DF provided by two OAs, the next larger OA must be chosen. Here for experimentation, L_{16} Taguchi Orthogonal Array for three process parameters and their four levels was selected. The L_{16} orthogonal array for final experiment is as shown in Table 4.1.

Table 4.1: L_{16} Orthogonal Array of Final experiment

Expt. No.	Laser Power (W)	Scanning speed(mm/min)	Gas pressure (bar)
1	1500	1700	0.8
2	1500	1750	1
3	1500	1800	1.2
4	1500	1850	1.4
5	1600	1700	1
6	1600	1750	0.8
7	1600	1800	1.4
8	1600	1850	1.2
9	1700	1700	1.2
10	1700	1750	1.4
11	1700	1800	0.8
12	1700	1850	1
13	1800	1700	1.4
14	1800	1750	1.2
15	1800	1800	1
16	1800	1850	0.8

Figure 5: Experiments

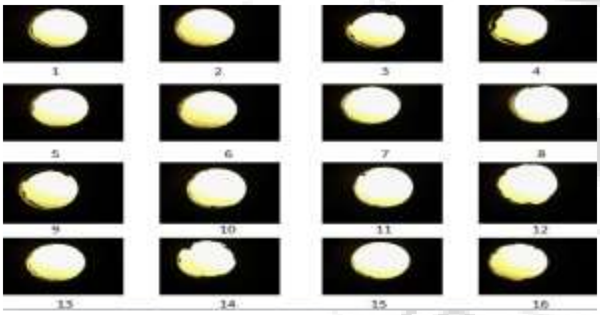
Figure 4: Images of laser drilled hole at entrance of hole

4.3 Readings of Experimentation

Readings of diameters at entrance and exit of hole was taken, four readings were taken and then averaged for the analysis purpose.

Table 4.2: Experimental Reading for Entrance Hole Diameter

Sr. No.	Hole Entrance Diameters	Average Value
1	6.04+6.02+6.02+6	6.020
2	6.06+6.02+6.04+6.04	6.040
3	6.10+6.06+6.04+6	6.010
4	6.10+6.18+6.08+6.06	6.105
5	6.12+6.07+6.14+6	6.080
6	6.06+6+6.04+6.10	6.010
7	6.0+6.01+6.03+6.02	6.015
8	6.08+6.06+6.03+6.08	6.075
9	6.02+6.08+6.06+6.04	6.100
10	6.18+6.08+6.08+6.16	6.125
11	6.0+6.01+6.02+6.01	6.010
12	6.34+6.26+6.36+6.24	6.300
13	6.04+6.14+6.06+6.10	6.080
14	6.10+6.12+6.14+6.12	6.120
15	6.14+6.12+6.12+6.18	6.140
16	6.16+6.16+6.18+6.20	6.175

Table 4.3: Experimental Readings for Exit Hole Diameter

Sr. No.	Hole Exit Diameters	Average Value
1	6.08+6.08+6.20+6.18	6.013
2	6.12+6.18+6.10+6.08	6.012
3	6.06+5.86+5.9+5.7	5.880
4	6.02+6.04+6.03+6.03	6.030
5	6.08+6.1+6+6.04	6.055
6	5.98+5.86+5.96+6.08	5.970
7	5.92+5.98+6.10+6.04	6.010
8	5.80+6.08+6.16+6	6.010
9	5.98+6.44+5.68+5.50	5.900
10	6.08+6.08+6.04+6.10	6.075
11	6.03+5.90+6.02+6.01	5.985
12	6.48+6.30+6.58+5.90	6.160
13	5.90+6.16+6.10+6.16	6.070
14	6.18+6.5+5.62+5.6	5.975
15	6.13+6.12+6.08+6.06	6.097
16	5.98+5.99+6.3+6.16	6.107

4.4. Measurement of Responses

Responses like taper angle ,surface roughness was measured and there S/N ratios were plotted in graphs and the analysis was done that how the input parameters are affecting the response parameters.

4.4.1. TAPER ANGLE OF HOLE

Taper of hole is given by- Taper Angle (θ) = $\tan^{-1}$((Dent — Dext) / 2t) ,where Dent and Dext are diameter at entrance and exit of hole respectively.

Table 4.4: Experimental Readings for Taper angle

EXP NO	Laser Power (watt)	FEED (mm/min)	GAS (bar)	ENT DIA	EXIT DIA	TAPER
1	1500	1700	0.8	6.0200	6.013	0.05013
2	1500	1750	1	6.0400	6.012	0.20053
3	1500	1800	1.2	6.0100	5.990	0.93097
4	1500	1850	1.4	6.1050	6.030	0.53713
5	1600	1700	1	6.0800	6.055	0.17904
6	1600	1750	0.8	6.0100	5.970	0.28647
7	1600	1800	1.4	6.0150	6.010	0.03580
8	1600	1850	1.2	6.0750	6.010	0.46551
9	1700	1700	1.2	6.1000	5.900	1.43209
10	1700	1750	1.4	6.1250	6.075	0.35809
11	1700	1800	0.8	6.0100	5.985	0.17904
12	1700	1850	1	6.3000	6.160	1.00257
13	1800	1700	1.4	6.0800	6.070	0.07161
14	1800	1750	1.2	6.1200	5.975	1.03837
15	1800	1800	1	6.1400	6.097	0.30796
16	1800	1850	0.8	6.1750	6.107	0.48700

Table 4.5: Anova for taper angle

Source	DF	ADJ SS	ADJ MS	F	P	%C
Laser Power	3	0.5130	0.17101	5.03	0.236	19.8
Scanning Speed	3	0.1444	0.04814	0.53	0.680	5.58
Gas Pressure	3	1.3808	0.46026	1.87	0.045	53.3
Error	6					21.2
Total	15					100

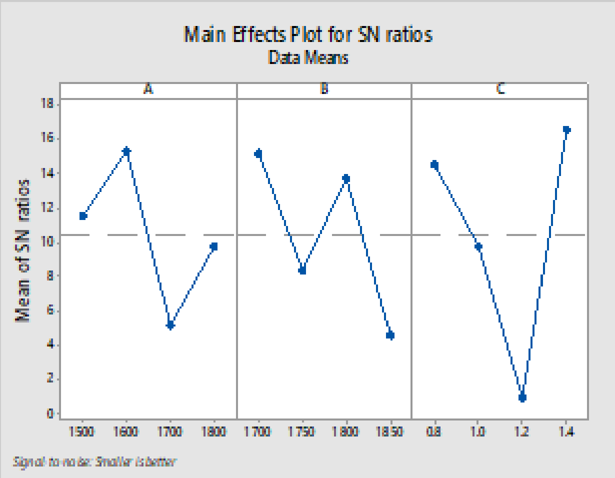

Figure 6: Main effect plots of Signal to Noise Ratios for Taper angle

Table 4.6: Response Table of Signal to Noise Ratios for Taper angle

Level	Laser Power (W)	Scanning Speed (mm/min)	Gas pressure(bar)
1	11.4935	15.1800	14.5117
2	15.3408	8.3520	9.7763
3	5.1799	13.6787	0.9541
4	9.7633	4.5667	16.5354
Delta	10.1609	10.6133	15.5813
Rank	3	2	1

Conclusions

1) The Anova results show that for taper angle, gas pressure is more significant parameter than the other two.
2) Gas pressure is more contributing for the experiments more as compared to others.
3) While the S/N ratios for taper angle also shows that gas pressure is having a rank 1 i.e., most influencing parameter among all. Whereas scanning speed, gas pressure are not more influencing ones.
4) The optimum results are obtained at 7th experiment where laser power is 1600 watt, 1800 mm/min scanning speed, 1.4 bar gas pressure we have least taper angle 0.03580 degrees.
5) By observing S/N ratio plot laser power at 1600 watt, scanning speed at 1700 mm/min ,gas pressure at 1.4 bar are likely to be optimum values for machining.
6) Higher values of gas pressure are generally recommended for low taper angles.

4.4.2. Surface Roughness of Hole

a) Surface roughness is one of the important parameter that can be used to judge the quality of hole produced by different machining processes.
b) In laser drilling, surface roughness of hole can be used as a one of the response variable.
c) Laser drilled hole can be categorised as good hole as if its roughness value is low.
d) Lower the better is used in the case of surface roughness lower value is been taken as optimum.
e) For measuring the values of surface roughness evaluation length of 1.25 mm was taken with 5 intervals in 0.25mm cutoff length. The values of Ra were noted down with graphs from Taylor hobson surface roughness tester.

Table 4.7: Experimental Readings for surface roughness

Expt . No.	Reading 1	Reading 2	Reading 3	Reading 4	(Ra) value
1	0.84	0.64	0.74	0.74	0.740
2	0.54	0.36	0.40	0.44	1.740
3	1.14	1.24	1.11	1.17	1.165
4	0.66	0.72	0.40	0.56	0.585
5	0.68	0.62	0.70	0.62	0.655
6	1.12	1.24	1.17	1.09	1.155
7	0.06	0.24	0.16	0.18	0.160
8	0.15	0.16	0.25	0.18	0.185
9	1.32	1.32	1.48	1.60	1.430
10	2.02	1.92	1.68	1.80	1.855
11	0.86	0.90	0.96	0.88	0.900
12	0.88	0.60	0.42	0.94	0.710
13	0.62	0.74	0.76	0.78	0.725
14	1.10	0.52	0.62	0.92	0.790
15	0.36	0.48	0.44	0.56	0.460
16	0.37	0.47	0.44	0.54	0.455

Table 4.8: Anova for Surface Roughness

Source	DF	ADJ SS	ADJ MS	F	P	%C
Laser Power	3	1.3529	0.4509	5.10	0.043	36.3
Scanning Speed	3	1.8141	0.6047	6.84	0.023	48.7
Gas Pressure	3	0.0203	0.0203	0.08	0.970	0.55
Error	6	0.5423	0.0884			14.2
Total	15					100

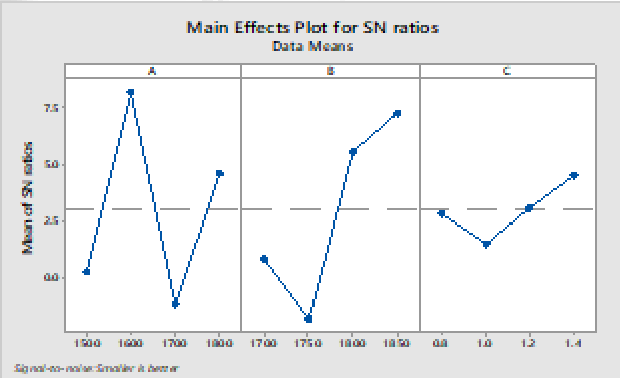

Figure 7: Main effect plots of Signal to Noise Ratios for surface

Table 4.9: Response Table of Signal to Noise Ratios for Surface roughness

Level	Laser Power (W)	Scanning speed(mm/min)	Gas Pressure (bar)
1	0.2837	1.4943	2.2797
2	8.2494	-2.3455	2.1460
3	-1.1459	5.5628	3.0677
4	4.6063	7.2820	4.5002
Delta	9.3962	9.6275	2.3542
Rank	2	1	3

Conclusions

1) The Anova results show that for Surface roughness, Scanning speed is most significant parameter after that laser power is significant and gas pressure is not affecting that much.

2) Scanning speed and laser power is more contributing for the experiments.
3) While the S/N ratios for surface roughness also shows that Scanning speed is having a rank 1 i.e., most influencing parameter among all. Whereas gas pressure is not more influencing one.
4) The optimum results are obtained at 7^{th} experiment where laser power is 1600 watt, 1800 mm/min scanning speed, 1.4 bar gas pressure we have least surface roughness 0.160 microns.
5) By observing S/N ratio plot laser power at 1600 watt, scanning speed at 1700 mm/min ,gas pressure at 1.4 bar are likely to be optimum values for machining.
6) Higher values of scanning speed are generally recommended for low surface roughness.

References

[1] Dr. Ulrich Durr, "Laser Drilling in Industrial Use Strategies and Applications," Laser Technik, May 2008, pp. 57-59.
[2] George Chryssolouris, "Laser Machining Theory and Practice," Mechanical Engineering Series Book, Springer Publication, pp. 1, 2.
[3] Bekir Sami Yilbas, book of "Laser Drilling Practical applications," Manufacturing and surface engineering, Springer Publication, pp. vii, 1, 2, 38, 39, 42, 49.
[4] Jeb Collins and Pierre Gremaud, " A Simple Model for Laser Drilling," Mathematics and Computers in Simulation 81, 2011, pp. 1541-1552.
[5] M. Boutinguizaa, J. Poua, F. Lusquinosa, F. Quinteroa, R. Sotoa, M. Perez-Amora, K. Watkinsb and W.M. Steen, "CO_2 laser Cutting of Slate," Optics and Lasers Engineering, 2002, pp. 15–25.
[6] K. Abdel Ghany and M. Newishy, "Cutting of 1.2 mm Thick Austenitic SS sheet using pulsed and CW Nd:YAG laser," Journal of Materials Processing Technology 168, 2005, pp. 438–447.
[7] Yeo C. Y., Tam S. C., Jana, S. and Lau M. W., "A technical review of the laser drilling of aerospace materials," Journal of Materials Processing Technology, vol. 42(1), 1994, pp. 15- 49.
[8] Tansel I., Rodriguez O., Trujillo M., Paz E. and Li W., "Micro-end-milling—I. Wear 102 and breakage," International Journal of Machine Tools and Manufacture, vol. 38(12), 1998, pp. 1419-1436.
[9] Chryssolouris G., Bredt J., Kordas S. and Wilson E., "Theoretical aspects of a laser machine tool," Journal of Manufacturing Science and Engineering, vol. 110(1), 1988, pp. 65-70.
[10] G.K.L. Ng and L. Li, "The Effect of Laser Peak Power and Pulse Width on the Hole Geometry Repeatability in Laser Percussion Drilling," Optics & Laser Technology 33 , 2001, pp. 393–402.
[11] A. Bharatish, H.N. Murthy, B. Anand, C.D. Madhusoodana, G.S. Praveena and M. Krishna, "Characterization of hole circularity and heat affected zone in pulsed CO_2 laser drilling of alumina ceramics," Optics & Laser Technology, 2013, pp. 22–32.
[12] Furat I. Hussein, Ziad A. Taha, Thaier A. Tawfiq and Ahmed B. Jawad, "Laser Hole Drilling of Stainless Steel 321H and Steel 33 Using 3D CO_2 Laser CNC Machine," Iraqui Journal of Laser, Vol. 10, 2011, pp. 15-21.
[13] HenrikkiPantsar, Hans Herfurth, Stefan Heinemann, Petri Laakso, RaimoPenttila, Yi Liu and GolamNewaz, "Laser Microvia Drilling and Ablation of Silicon using 355Nm Pico and Nanosecond Pulses," Laser Microprocessing Conference, 2008, pp. 278-287.
[14] S. Bandyopadhyay, HinaGokhale, J.K. SarinSundar, G. Sundararajan and S.V. Joshi, "A statistical approach to determine process parameter impact in Nd:YAG laser drilling of IN718 and Ti-6Al-4V sheets," Optics and Lasers in Engineering, vol. 43, 2005, pp. 163–182.
[15] El-Taweel T. A., Abdel-Maaboud A. M., Azzam B. S. and Mohammad A.E., "Parametric studies on the CO_2 laser cutting of kevlar-49 composite," The ternational Journal of Advanced Manufacturing Technology, vol. 40 (9- 10), 2009, pp. 907- 917.
[16] TosunN.,"Determination of optimum parameters for multi-performance characteristics in drilling by using grey relational analysis," The International Journal of Advanced Manufacturing Technology, vol. 28(5-6), 2006, pp. 450- 455.
[17] S. Nagesh, H.N. Narasimha Murthy, Ratna Pal, M. Krishna and B. S. Satyanarayana, "Influence of Nano Fillers on the Quality of CO_2 Laser Drilling in Vinylester/ Glass using Orthogonal Array Experiments and Grey Relational Analysis," Optics & Laser Technology 69, 2015, pp. 23–33.
[18] I.A. Choudhury, W.C. Chong and G. Vahid, "Hole qualities in laser trepanning of polymeric materials," Optics and Lasers in Engineering, vol. 50, 2012, pp. 1297–1305.

Author Profile

Siddhant Gade is M.Tech student in Mechanical- Production Engineering in Walchand College of Engineering, Sangli. He Completed his graduation in mechanical engineering in 2016 from Solapur University, Solapur

Dr. K. H. Inamdar is Professor in Department of Mechanical Engineering, WCE, Sangli. He has published more than 80 Technical papers in various National /International conference as well as journals. His area of interest is Quality control and he acquired patent related to it.