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# Performance analysis of process variables on laser beam machining of inconel-718 alloy

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**Abstract.** Carbon-dioxide laser beam machining (LBM) is used for machining intricate shapes and hard materials which are inconceivable with conventional machining methods. Inconel 718 finds its prime applications in manufacturing high pressure turbine components and structural components of aerospace industry.Inconel 718 alloy exhibits superior physical and mechanical properties at elevated temperature, Strength-to-density ratio and higher corrosion resistance. The objective of the current work is to determine the optimal setting of the process parameters like laser power, cutting speed, gas pressure while machining Inconel-718 material using oxygen gas. The experiment was conducted using Taguchi $L_9$ orthogonal array. A square washer with four holes of diameter 8 mm and one hole of diameter 64 mm was machined using laser beam machining and the best combination of process parameters to acquire better response parameters is computed. The optimized value of surface roughness was found to be 3.5µm and similarly material removal rate to be 45.56 $m^3$/min when operated at 2.1m/min cutting speed, cut of type rough, 1mm of focal point and 4000bar gas pressure, The effect of input variables on various response parameters namely surface roughness (Ra), Heat affected zone thickness (HAZ), material removal rate (MRR), Taper, Circularity, hardness were studied. Morphology of the machined surface was investigated using SEM analysis.

## 1. Introduction

Inconel-718 an alloy of Nickel is used in this work considering its exceptional physical and chemical properties. It exhibits high strength at both extremes. Lowest goes upto cryogenic temperature and the highest goes up to 704˚C/1300˚F.Throughout this entire range it exhibits exceptionally high tensile, yield and creep-rupture properties. It also shows excellent impact and tensile strength. It exhibits good corrosion resistance which includes resistance to oxidation. Because of its easy fabrication into increasingly intricate parts, the material paves way for high-performance applications. Nickel alloys are available in many forms; Ingots, bars, billets, plate, seamless pipes, wire, tubes. Inconel-718 finds its application in various Industries out of which it is extensively used in aeronautical industries for manufacturing the engine parts, blades, turbines, high speed airframe parts and cryogenic tanks [1]. In this work Laser Beam Machining (LBM) is used for machining the workpiece (WP).The working principle of LBM is such that, a work piece (WP) is machined using high energy laser beams on the surface of WP. The heat which is absorbed by thesurface vaporizes the material and helps in machining. LBM has its applications in machining minute slits up to 5 microns in ceramic materials, composites and metals. Openings of 1.5mm distance across for metallic and non-metallic materials [2]. The procedure can be performed on ceramics, non-metals, organics, plastic, metals and so forth. Gaps with a measurement of under 0.25 mm can likewise be made. Other materials that can be lasered are food products form glass, die board, alumina, silicon nitride, polymer and matrix composites, titanium and aluminium based alloy, paper, rubber, tile. The prime purpose of this work is to analyse the circularity, surface roughness, material removal rate(MRR), Rockwell hardness, taper, heat affected zone thickness(HAZ) on Inconel 718 and to identify the optimum input variables to attain satisfactory outcome using Taguchi-grey relational analysis.

A literature review was conducted on the recent research works on LBM and they are taken as the references and explained below. Singh et al. [3]carried out the effect of process parameters like gas pressure, cutting speed and laser power on HAZ of the PMMA (Polymethyl methacrylate) and concluded that lower the cutting speed, higher the HAZ similarly higher the laser power higher the HAZ. Abhimanyu and Satyanarayana[4] carried a work to optimize the cut quality of mild steel during the process of pulsed $CO_2$ laser cutting. With various input process parameters like cutting speed, laser power and material thickness the output parameters were chosen to be surface hardness and edge surface roughness. They finally deduced that RSM to be a most suitable method for the identifying and developing significant relationships between the input variables. Prabhakaran et al. [5]carried out an investigation on the effect of laser cutting on a 2mm thick nonferrous metal sheet i.e. BS 1100 using $CO_2$ laser. The analysis was on the effects of the control factors like cutting speed, laser power, standoff distance and assist gas pressure on the surface roughness, cut quality characteristics and kerf width resulted with an improved Surface Roughness ($R_a$). Senthilkumar et al. [6] investigated the outcome of parameters linked with $CO_2$ laser cutting of Aluminum plate. The parameters like power, stand-off distance, cutting speed had major impact over kerf width and surface roughness($R_a$). While, the impact of assist gas pressure over kerf width and surface roughness were less significant. Argade and Arakcrinta[7] studied the effect of input variables such asinput power, gas pressure and cutting speed of $CO_2$ laser cutting on the surface integrity of AISI 409 using laser beam. The response parameters used to measure the quality of the cut are surface roughness and kerf width. DOE was formulated using a Taguchi method design. Cutting speed & gas pressure were the most determining factors on surface roughness, laser power & gas pressure were responsible for kerf width. Leone et al. [8] investigated the Nd:YAG laser cutting of 6061 -T6 aluminum alloy sheet. Maximum cutting speeds was measured by linear scans of pulse duration, various cutting direction and maximum average power. Cutting speed, pulse direction, beam travel direction was varied to perform the cutting test. Madic et al. [9] used L25 orthogonal array in order to determine the optimized cutting parameter such as assist gas pressure, laser power and cutting speed for reducing the $R_a$in $CO_2$ laser cutting process. It is found that the surface roughness decreases with an increase in cutting speed and laser power increases with an increase in assist gas pressure. Prajapati et al. [10] found that the contribution of work piece thickness and cutting speed was high in surface roughness when compared to laser power. Laser machining parameters were studied. The experiment was conducted using Taguchi L27 orthogonal array and ANOVA was performed and optimized parameter was chosen by S/N ratio. Madia and Patel [11] studied the variation of surface roughness on 1mm brass sheet with focal length and laser power using assist gas oxygen. ANOVA reveals that focal length have significant effect on cutting speed and surface roughness.Manoj Samson et al. [19] carried out an experimental investigation on the impact of MRR, Surface Roughness and Dimensional change on Hastelloy C22 using Electro Chemical Machining by varying the process parameters. The best values were obtained using Taguchi Grey Relational Analysis. Manoj Samson et al.[18] made a comparative study on the quality of surface finish and MRR obtained when the assist gas in a Laser Beam Machining is switched between oxygen and nitrogen on a Titanium Alloy. It was concluded that nitrogen gave better results when compared to that of oxygen.

**Figure 1.** Principle of laser machine.

**Figure 2.** Workbench of $CO_2$ Laser.

## 2. Materials and methods

Inconel-718 an alloy of nickel is chosen considering its competitive properties to withstand and produce optimum output using the non-conventional machining technique. The composition has been studied during the literature survey [12]. Laser beam machining is done using the $CO_2$ laser cutting system. In this oxygen is used as the assist gas. The composition of Inconel-718 is found from the literature review [13].After the selection of material and machining techniques, the process parameters such as gas pressure, laserpower, cutting speed were selected. Using Taguchi method the optimum setting of input variables is formulated. Gas pressure, power and cutting speed of the laser have been considered as the variable input process parameters. To determine the cutting range for the material, experiments have been carried out with some values as reference form other materials which resemble Inconel in both physical and chemical composition. Trial cut values are shown in the Table 2.1

**Table 2.1.** Trial Cut Values.

| S.NO | Power(W) | Speed(mm/min) | Gas Pressure(Bar) |
|---|---|---|---|
| **1** | 1800 | 3000 | 3 |
| **2** | 2200 | 5000 | 3.5 |
| **3** | 1500 | 2500 | 2 |

Standoff distance is limited to 1.5mm.Frequency of the laser which is 1200 HZ in the machine which was used to conduct the experiments.The focal point for machine is 200mm. Assist gas used in the experiments is oxygen. The above said parameters were chosen to be fixed parameters due to the constraints of the parts and the capabilities of the machine. Design of experiments (DOE) is done to find cause-and-effect relationships. For optimizing the output this information is needed to manage process inputs. For this work Taguchi analysis is chosen due to its simplicity and easy adaptability, for optimizing the process variables.

**Figure 3.** Inconel 718.

Inconel 718 is represented in Fig.3.To determine the cutting range for the material, experiments have been carried out with some values as reference form other materials which resemble Inconel in both physical and chemical composition. The Procedure of the DOE is referred from the literature review [14]. L9 orthogonal array is performed to arrive at the optimum value with minimal trails using Minitab software.

The steps involved in Grey Relational Analysis and Grey Relational Optimization are referred from the literature survey [15].

**Steps for Performing Taguchi Grey Relational Analysis:**

Step 1: The S/N ratio of the performance characteristics was calculated and normalized.

Step 2: Deviation sequences and the grey relational coefficient for each responses was evaluated.

Step 3: Grey relational grade was obtained by averaging the grey relational coefficient corresponding to performance characteristics and it was ranked.

Step 4: The main effects of the factors on grey relational grade was evaluated and the optimal combination of parameters was obtained.

**Table 2.2.** Levels Obtained By Taguchi Method.

| Specimen | Power(W) | Speed (mm/min) | Gas Pressure (Bar) |
|---|---|---|---|
| **1** | 1500 | 2500 | 2.0 |
| **2** | 1500 | 3000 | 3.0 |
| **3** | 1500 | 5000 | 3.5 |
| **4** | 1800 | 2500 | 3.0 |
| **5** | 1800 | 3000 | 3.5 |
| **6** | 1800 | 5000 | 2.0 |
| **7** | 2200 | 2500 | 3.5 |
| **8** | 2200 | 3000 | 2.0 |
| **9** | 2200 | 5000 | 3.0 |

## 3. RESULT AND DISCUSSION

Material removal rate if found using the difference between the weights of the workpiece before and after the process for the machining period. From Table 3.1 it has been observed that for particular power when the gas pressure and speed areincreased, the MRR value increases. Thus the specimen 3 with the input parameter mentioned in table 2.2 has the highest MRR value of 79.1412 g/min. Surface roughness is high when the power is low for specimen 1 and when the power is high the surface roughness value is less for specimen 8. Hardness value is higher for specimen 6 and lower for specimen 3. Heat affected zone thickness has been calculated using machine vision and found that the maximum thickness of the HAZ at top is to be 0.621 for the specimen 3 and at the bottom is for the specimen 1. The circularity values for top and bottom are low for specimen 4 and the taper value is found to be less in specimen 8. SEM analysis captures the HAZ of the work piece and the images of specimens are shown in figure 4-6. It is found that the surface of the specimen 5 is not even. It has pits and holes which bring in ductile fractures. Specimen 8 has an even surface finish. Whereas the specimen 9 has less pits and holes, this ensures a minute ductile fracture.

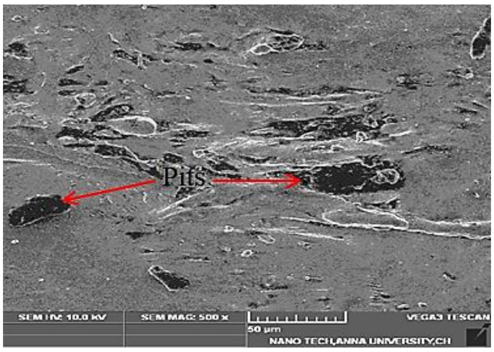


**Figure 4.** Specimen 5.

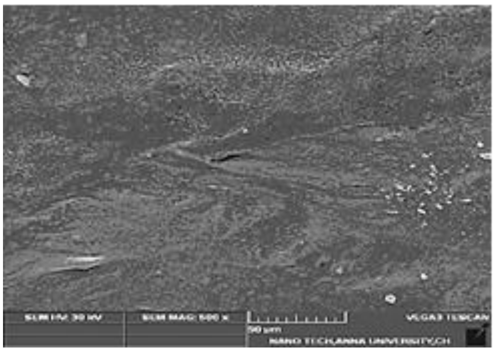

**Figure 5.**Specimen 8.

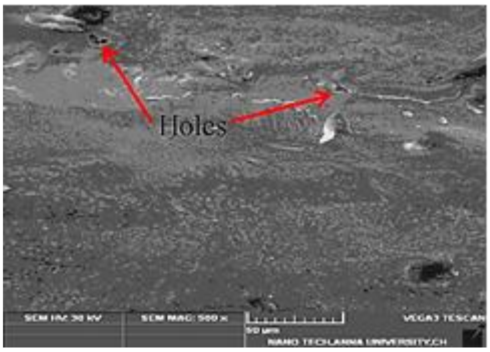


**Figure 6.** Specimen 9.

**Table 3.1.** Results of the process.

| Specimen | Material Removal Rate(MRR) | Rockwell Hardness (HRC) | HAZ Thickness Top | HAZ Thickness Bottom | Surface Roughness (Ra) |
|---|---|---|---|---|---|
| **1** | 61.9492 | 25.53 | 0.2505 | 0.6425 | 2.6567 |
| **2** | 66.6191 | 28.3 | 0.4665 | 0.2535 | 2.1686 |
| **3** | 79.1412 | 21.8 | 0.621 | 0.2595 | 2.062 |
| **4** | 63.6506 | 31.9 | 0.2795 | 0.514 | 1.513 |
| **5** | 66.4572 | 30.3 | 0.4245 | 0.2275 | 3.0375 |
| **6** | 76.5758 | 32.3 | 0.427 | 0.241 | 1.2314 |
| **7** | 64.5628 | 28.5 | 0.245 | 0.421 | 1.4012 |

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| | | | | | |
|---|---|---|---|---|---|
| **8** | 66.2529 | 31.6 | 0.2705 | 0.571 | 1.1574 |
| **9** | 77.8093 | 23.5 | 0.226 | 0.44 | 2.0254 |

**Heat Affected Zone thickness top** (Specimen 1) = (8.578-8.077)/2

= 0.2505 mm

**Heat Affected Zone thickness bottom** (Specimen 1) = (9.377-8.092)/2

= 0.6425 mm

**Table 3.2.** Circularity.

| Specimen | Circularity top(mm) | Circularity bottom(mm) | Taper |
|---|---|---|---|
| **1** | 0.054 | 0.052 | 0.00441 |
| **2** | 0.076 | 0.059 | 0.00882 |
| **3** | 0.12 | 0.123 | 0.00264 |
| **4** | 0.046 | 0.032 | 0.00735 |
| **5** | 0.119 | 0.094 | 0.000882 |
| **6** | 0.075 | 0.083 | 0.00411 |
| **7** | 0.179 | 0.164 | 0.00352 |
| **8** | 0.124 | 0.124 | 0.000588 |
| **9** | 0.124 | 0.126 | 0.00441 |

**Taper** (Specimen 1) = (8.092-8.077)/ (2*1.7

= 0.0044

**Grey – Taguchi Relational Analysis:**

**Specimen 1 (example)**

- **Step 1: Calculation of S/N ratio**

S/N RATIO OF higher the better value (MRR) = $-10*\log(1/x)\,\Sigma(1/Y^2)$

$= -10*\log(1/61.9492^2)$

= 35.84071

- **Step 2: Calculation of Grey relation grade**

GC = (**Δ** min + δ **Δ**max)/( **Δ** + δ **Δ**max)

Grey relation grade (MRR) = (0+0.5)/ (1+0.5)

= 0.333333

**Table 3.3.** Grade Rank for Response Parameters.

| specimen | GC (MRR) | GC (Ra) | GC (Circularity) | GC (Ht) | GC (Taper) | GR GRADE | RANK |
|---|---|---|---|---|---|---|---|
| **1** | 0.3333 | 0.7826 | 0.3617 | 0.3576 | 0.6614 | 0.4993 | 3 |
| **2** | 0.4155 | 0.5887 | 0.4422 | 0.6385 | 1 | 0.6170 | 2 |
| **3** | 1 | 0.5546 | 0.6294 | 1 | 0.5288 | 0.7425 | 1 |
| **4** | 0.3598 | 0.4090 | 0.3333 | 0.3876 | 0.8813 | 0.4742 | 8 |
| **5** | 0.4121 | 1 | 0.6246 | 0.5705 | 0.3702 | 0.5955 | 5 |
| **6** | 0.7879 | 0.3482 | 0.4381 | 0.5743 | 0.6394 | 0.5576 | 6 |
| **7** | 0.3755 | 0.3840 | 1 | 0.3520 | 0.5958 | 0.5415 | 7 |
| **8** | 0.4079 | 0.3333 | 0.6491 | 0.3781 | 0.3333 | 0.4203 | 9 |
| **9** | 0.8782 | 0.5434 | 0.6491 | 0.3333 | 0.6614 | 0.6131 | 4 |

After gaining the optimized values for Surface Roughness, Material removal rate (MRR), Rockwell Hardness, HAZ thickness, Taper and Circularity test from Grey – relation analysis, confirmation test was carried with the same parameters in order to verify the certainty of the obtained results. With respect to the 95% confidence limit, the result shows that there is 4.67% and 3.25% error in the values for MRR and surface roughness respectively.

## 4. Conclusion

In this work, Nickel alloy (Inconel-718) is machined using $CO_2$. LBM based on its applications in the field of Engineering. The input parameters likecutting speed,Gas pressure andLaser powerare varied to arrive at the optimum values of response parameters like MRR,HAZ thickness, Surface roughness, Taper, Circularity and Rockwell Hardness. Taguchi-Grey analysis is used for optimizing the machining parameters. The optimal blends of input variables to obtain better response parameters are found. 45.56$m^3$/min was found to be the optimized satisfactory value of MRR and 3.5µm for surface roughness under the condition of 2.1m/min cutting speed, 4000bar gas pressure, cut of type rough and focal point of 1mm.Cutting speed and pressure play a vital role for getting a betterMRR. And Focal point and type of cut for getting better surface roughness.35% increase in surface roughness and 45% increase in MRR was obtained by using nitrogen as assist gas instead of oxygen in Co2 LBM.The confirmation test was done verify the obtained results. And the results reveal the error percentage for MRR to be 4.67% and 3.25% for surface roughness.

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