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# Sensitivity Analysis of Process Parameters in Submerged Laser beam Cutting on Inconel 625 Superalloy

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**Abstract**

laser beam submerged cutting of inconel 625 super alloy has been conducted here to study the sensitivity of machining response. sensitivity analysis of machining criteria in terms of kerf width on controllable process variables, such as lamp current, pulse frequency, duty cycle, cutting speed, height of water column during laser beam cutting of inconel 625 superalloy at submerged condition has been performed.. The central composite design (CCD) technique based on response surface methodology (RSM) is employed here to carry out the experiments to achieve optimum responses with a reduced number of experiments. The developed mathematical models are tested by analysis-of-variance (ANOVA) method to check their adequacy.

**Keywords:** Underwater Laser cutting; Inconel 625; Kerf width; Response surface methodology.

## 1. INTRODUCTION

Inconel 625 is a nickel based superalloy which have extensive use in aerospace, petrochemical and marine industries, due to it's properties like high thermal strength, high fatigue strength, very good oxidation and corrosion resistant at hostile environment. Presence of molybdenum and niobium in the nickel-chromium matrix is the reason behind great mechanical characteristics of Inconel 625 superalloy. Mechanical property, i.e. high toughness makes it difficult to machine material. Laser based thermal ablation process is a suitable alternative to process those kind of superalloys in micro domain [1]. Laser beam microcutting is a two dimensional non conventional machining procedure where material is removed by thermal or athermal ablation in micron range to produce any kind of normal or complicated shape. Small spot diameter, short or ultra short wavelength, high peak power, high energy density and good focusability makes pulsed Nd:YAG laser more advantageous over other laser process systems used in industries. An analytical model is developed by Ahmed *et.al.* to investigate the effect of beam shape on melt pool characteristics during laser surface melting of Inconel 625[2]. Quality aspects in form of HAZ width, kerf width, dross free neighbourhood of machining zone in desired form is very difficult to get during laser microcutting of superalloys. Selections of cutting parameters along with assist medium are the most dominating factors to get desired cut profile during pulsed laser beam microcutting operation. Some previous researchers used different assisted medium to get desired machining characteristics. Better natural convection along with change in refractive index during underwater laser machining results in narrow heat affected zone along with spatter free adjacent area of irradiation and less amount of debris spread in environment. Material removal is enhanced due to reduction in temperature gradient and more turbulence at in the operational zone during submerged machining zone which creates cleaner kerf. In different kind of waterjet assisted and underwater machining procedure, laser machining at submerged condition is said to the simplest one among the others [3]. Pressure dynamics in machining zone occurs during underwater laser beam machining of metal has been investigated by Ageev et.al.[4]. Surface quality and geometric precision of a laser machined SiC material in wet environment is better than processed in air [5]. Smaller HAZ with narrow kerf and lower surface roughness have been achieved by Muhammad et al. during wet laser profile cutting of thin stainless steel tube by using fibre laser [6]. The effect of surrounding medium along with scanning speed water on machining performance, i.e., surface roughness, depth of cut and kerf width have been investigate by Behera et.al. during microchannelling of SS 304 by pulsed Nd:YAG laser with 534 nm wavelength [7]. A waterjet assisted underwater laser beam system has been designed and developed by Mullick et. al. to study the parametric effects during cuttings of AISI 304 steel sheet of 1.5 mm thickness at 13.7 mm depth in water by 2 kW CW Yb fibre laser [8]. In absence of appropriate technology guidance of laser submerged microcutting of aforesaid nickel based superalloy till date, an experimental investigation has been conducted, a in depth study has been conducted on Inconel 625 superalloy by laser ablation at submerged condition.

In this paper laser beam cutting of inconel 625 super alloy at submerged condition has been carried out followed by sensitivity analysis of machining characteristic on different controllable process parameters. Central composite design technique of response surface methodology has been chosen to design and perform the experiments laser microcutting of Inconel 625 at submerged condition. Height of water column, lamp current, pulse frequency, Duty cycle and cutting speed are selected as controllable process variables whereas kerf width is selected as machining response. Developed second order polynomial model has been further used to carry out sensitivity analysis to study the relative sensitivity of machining response on different process variables.

## 2. EXPERIMENTAL SETUP

A CNC-based pulsed Nd:YAG laser machining system with fixed wavelength (1064 nm) and spot diameter of 100 micron of Gaussian beam nature, manufactured by M/s Sahajanand Laser Technology, India, is used for the experiment. A special workpiece holding unit (designed and manufactured previously) is placed over the CNC controlled work table. Workpiece is held on the device in underwater condition by pouring water externally. Height of water column is measured by the dimension of slip gauge which is placed over the top surface of workpiece material. A steady state of water column is maintained during the experiment preciously as requirement. Inconel 625 superalloy with 8mm×8mm×0.9mm dimension has been considered as workpiece material for experimental study.

All the experiments are performed with deionised water at room temperature. Laser beam pass is kept constant at one.

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Schematic diagram of underwater laser beam machining set up is given in figure 1.

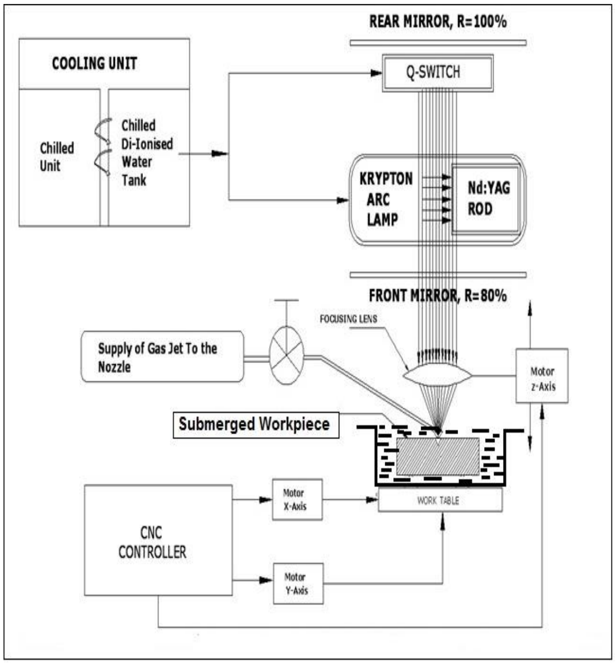

Fig 1. Schematic diagram of submerged laser beam machine [9].

Experiments have been carried out according to the central composite design based on response surface methodology (RSM). Response surface modelling is used to establish the mathematical relationship between the machining characteristics, $y_u$ and the various dependent process parameters,

$$y_u = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum_{i<j} \sum_{j=2}^{k} \beta_{ij} x_i x_j \quad ..(1)$$

Here $y_u$ is the corresponding response, e.g., kerf width. $x_i$ is the coded value of the i$^{th}$ machining parameter, k is the number of machining parameters and $\beta_i$, $\beta_{ii}$, $\beta_{ij}$ are the second order regression coefficients. Range of all dependent input process parameters for underwater laser machining i.e. height of water column, lamp current, pulse frequency, duty cycle and cutting speed are selected as one factor at a time approach during pilot experiments and listed in Table 1.

**Table 1 Process parameters levels**

| Process Parameter & Symbol | Levels | | | | |
|---|---|---|---|---|---|
| Lamp current (Amp) ($X_1$) | 20 | 22 | 24 | 26 | 28 |
| Pulse frequency (KHz) ($X_2$) | 2 | 4 | 6 | 8 | 10 |
| Duty cycle (%) ($X_3$) | 2 | 4 | 6 | 8 | 10 |
| Cutting speed (mm/sec) ($X_4$) | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 |
| Height of water Column (mm) ($X_5$) | 1 | 2 | 3 | 4 | 5 |

Image of, kerf width is captured by Olympus (STM 6) optical microscope at 20x magnification and measured by image analysis software has been provided with it. Top kerf width is measured at five different places for each kerf in the perpendicular direction of the laser beam movement and the average value of that is taken for further analysis. Kerf formation at different parameter settings is given in fig no. 2.

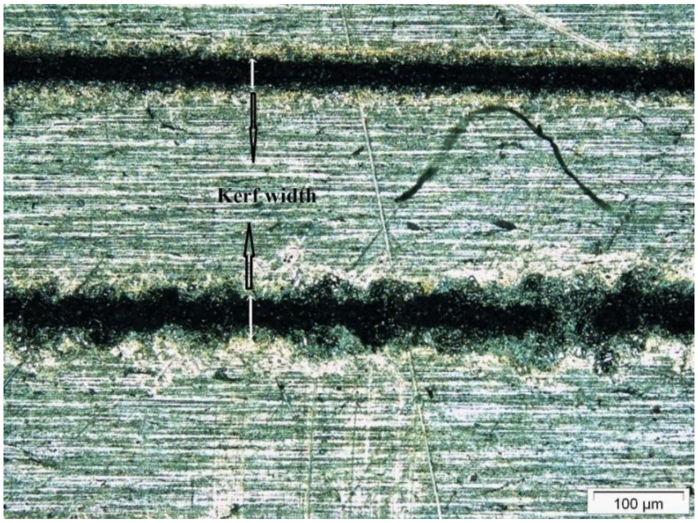

Fig 2. Kerf formation at different parameter settings.

## 3. EXPERIMENTAL RESULT

Experiments are conducted and the respective results are listed and given in the table no.2 given below.

**Table 2 Experimental results**

| Exp no. | kerf width (mm) | Exp no. | kerf width (mm) |
|---|---|---|---|
| 1 | 0.1346 | 27 | 0.0919 |
| 2 | 0.1836 | 28 | 0.0942 |
| 3 | 0.0933 | 29 | 0.1270 |
| 4 | 0.1039 | 30 | 0.2043 |
| 5 | 0.1141 | 31 | 0.0756 |
| 6 | 0.1886 | 32 | 0.0824 |
| 7 | 0.0860 | 33 | 0.0945 |
| 8 | 0.0963 | 34 | 0.1526 |
| 9 | 0.1193 | 35 | 0.1837 |
| 10 | 0.1571 | 36 | 0.0707 |
| 11 | 0.0912 | 37 | 0.1255 |
| 12 | 0.0910 | 38 | 0.1291 |
| 13 | 0.1052 | 39 | 0.1358 |
| 14 | 0.1640 | 40 | 0.1378 |
| 15 | 0.0843 | 41 | 0.1188 |
| 16 | 0.0854 | 42 | 0.1400 |
| 17 | 0.1355 | 43 | 0.1428 |
| 18 | 0.2294 | 44 | 0.1349 |
| 19 | 0.0941 | 45 | 0.1311 |
| 20 | 0.1156 | 46 | 0.1359 |
| 21 | 0.1477 | 47 | 0.1289 |
| 22 | 0.1997 | 48 | 0.1371 |
| 23 | 0.0866 | 49 | 0.1238 |
| 24 | 0.0949 | 50 | 0.1277 |
| 25 | 0.1301 | 51 | 0.1264 |
| 26 | 0.2176 | 52 | 0.1328 |

Minitab 17 Software is used for analysis of the measured kerf widths and determining the second order polynomial model with best fits. The developed polynomial model is given below,

$$KW=-0.925+0.0605X_1+0.0862X_2+0.0082X_3+0.0031X_4-0.0052X_5-0.000645X_1^2-0.000417X_2^2-0.000413X_3^2+0.00291X_4^2-0.00112X_5^2-0.003672X_1*X_2-0.000105X_1*X_3-0.00152X_1*X_4+0.001680X_1*X_5-0.000213X_2*X_3+0.00106X_2*X_4-0.003453X_2*X_5+0.00037X_3*X_4-0.000627X_3*X_5+0.00141X_4*X_5 \quad ..(2)$$

## 4. SENSITIVITY ANALYSIS

Sensitivity analysis shows if the objective function will increase or decrease with the change in the process parameters Sensitivity analysis determines which process parameter must be modified for getting improved result. Partial derivative of the objective function with respect of the variables is performed to get the sensitivity of objective function [10]. To obtained the sensitivity equation for kerf width with respect to lamp current equation no (2) is partially differentiated with respect to process parameters. Thus equations (3),(4),(5),(6) and (7) are the sensitivity equation of kerf width (*kw*) with respect to lamp current, pulse frequency, duty cycle, cutting speed and height of water column respectively.

$$dkw/dX1=0.0605-0.00129*X_1-0.003672*X_2-0.000105*X_3-0.00152*X_4+0.001680*X_5 \quad ..(3)$$

$$dkw/dX2=0.0862-0.000834*X_2-0.003672*X_1-0.000213*X_3+0.00106*X_4-0.003453*X_5 \quad ..(4)$$

$$dkw/dX3=0.0082-0.000826*X_3-0.000105*X_1-0.000213*X_2+0.00037*X_4-0.000627*X_5 \quad ..(5)$$

$$dkw/dX4=0.0031+0.00582*X_4-0.00152*X_1+0.00106*X_2+0.00037*X_3+0.00141*X_5 \quad ..(6)$$

$$dkw/dX5=-0.0052-0.00224*X_5+0.001680*X_1-0.003453*X_2-0.000627*X_3+0.00141*X_4 \quad ..(7)$$

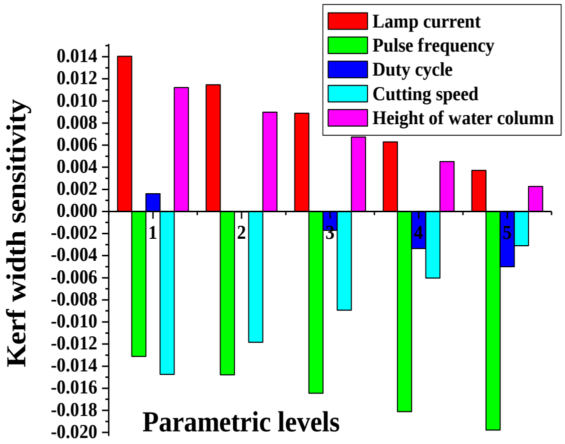

Fig 3. Sensitivity analysis of kerf width

From the fig, it is observed that kerf width have a positive sensitivity to height of water column and lamp current in terms of laser working power whereas negatively with pulse frequency and cutting speed. Kerf width shows a positive sensitivity with low duty cycle however changes to negative value with increase in duty cycle. Though the lamp current and height of water column shows a positive sensitivity it gradually decreases with increase in value for both. In submerged condition, initially the power density on the irradiate spot is not sufficient to melt and vaporize the material from the machining zone properly to produce clean kerf. A little change in lamp current add more power which enhance the material removal, results in better kerf width than previous condition. At the highest level of lamp current adequate amount of laser power is incorporated in the machining zone and a less wavy kerf width is visible. This may be the reason behind the observed phenomenon. In case of height of water column, at the lower level of water column turbulence at machining zone along with bubble burst in and around the irradiate spot and improper debris removal effects the kerf width mostly, results in waviness along the kerf. Whereas at the higher level, bubble burst is occurred at a distance from the machining zone which reduces the turbulence amount on the machining zone, and Increase in water volume by increase in water column results in more circulation water in & around the machining zone. Which along with bubbles expansion may helps uniform material removal from the machining zone. Thus creates a clean edge along the kerf. For the aforesaid reasons kerf width is more sensitive to water column height at lower level than higher range. It is evident from the fig. that at low pulse frequency sensitivity of kerf width comparatively more than high frequency, for that shows a negative sensitivity. Laser power density produce at irradiant spot at low pulse frequency is more than produced at higher pulse frequency for that sufficient laser power irradiates the top surface at low pulse frequency at submerged to produce desired kerf. Aforesaid situation may be the reason behind observed phenomenon. Though cutting speed shows a negative sensitivity to kerf width, it is observed that, change in kerf width is more at higher level of cutting speed. At higher cutting speed interaction time of laser beam with work substrate is less than that at lower cutting speed but turbulence at machining zone is more which dominates over the interaction time at submerged condition. Those may be reasons behind the observed graphical plot. From the graphical interpretation it can be said that duty cycle shows an unique tendency of sensitivity to kerf width. Sensitivity of kerf width to duty cycle firstly shows a positive tendency but negatively sensitive from mid value range within the chosen design spec. at lower duty cycle peak power more than that higher duty cycle which helps to enhance steady material removal due to more energy density at machining zone.

## 5. CONCLUSION

Underwater laser blind microcutting of inconel 625 sheet has been successfully performed here with aide of NIR pulsed Nd:YAG laser system. Central composite technique of response surface methodology is used to design the experiments within the predefined ranges of dependant process variable selected as per previously done pilot experiments and performed accordingly. Developed polynomial model is used to perform sensitivity analysis of machining response on controllable input process variable within the chosen design space. From the sensitivity analysis it has been concluded that all the process variables sensitive in respect to kerf width where pulse frequency and cutting speed shows negative sensitivity. Lamp current which represents laser working power and height of water column shows positive sensitivity. Sensitivity of kerf width to duty cycle indicates that it positive sensitive upto middle level, after that negatively sensitive with increase in duty cycle.

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