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A STUDY ON KERF TAPER AND SURFACE ROUGHNESS IN Nd: YAG LASER BEAM CUTTING BASED ON TAGUCHI METHOD

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ABSTRACT

This paper presents an investigation on the effect and optimization of laser cutting parameters on the performance characteristic during laser beam cutting of SUPERNI 718 thin sheet. Kerf taper and surface roughness is considered as performance characteristics. The experimental studies were conducted under varying oxygen pressure, pulse width, pulse frequency, and cutting speed. The settings of cutting parameters were determined by using Taguchi experimental design method. Analysis of variance (ANOVA) has been used to determine the level of significance on the kerf taper and surface roughness. The optimum cutting parameters was obtained by using the analysis of signal-to-noise (S/N) ratio. Confirmation experiments have been done to verify the optimum results and considerable improvement has been found for both quality characteristics using Taguchi methodology.

Keywords: *Laser Beam Cutting, SUPERNI 718, Taguchi Method, Kerf Taper, Surface Roughness.*

1. Introduction

Super alloys are used for manufacturing of those components which are required to retain their shape at elevated temperatures. Super alloys are mainly three types: iron based, cobalt based and nickel based. But the nickel based super alloys are being best suited for aeroengine applications.

Nickel based super alloy sheets in general and SUPERNI 718 sheet in particular, is used as casing for jet engines, aeroengine turbine blades, turbo charger, and pump body parts [1]. Due to the improved mechanical properties of nickel based super alloys sheets the complex profile cutting of these sheets are difficult by the conventional sheet cutting operations. Advanced sheet cutting processes (ASCPs) are well suited for cutting advanced difficult-to-cut sheet materials [2]. Laser beam cutting (LBC) is one of the widely used processes among all ASCPs for cutting complex profiles in thin sheets of conventional as well as difficult to cut materials. The material to be cut can be fragile, brittle, an electric conductor or an electrical insulator, hard or soft [3].

LBC, being a non-contact process, does not involve any mechanical cutting forces and tool wear. LBC is a thermal energy based cutting process which is executed by moving a focused laser beam on the surface of the workpiece with appropriate scanning speed. Oxygen gas is also supplied through a nozzle to remove the molten metal. LBC of sheetmetals has always been a major research area for getting the exceptionally good quality of cut [4-5]. There are many input parameters affecting the quality of laser cutting such as laser type and power, type and pressure of assist gas, cutting speed, sheet material composition and its thickness, and mode of operation of laser beam (Continuous or Pulsed mode). To achieve acceptable level of kerf quality characteristics, it is necessary to choose optimum combination of input process parameters [1, 2].

A lot of experimental and theoretical investigations have been done to analyze the effect of process parameters on cut geometry and cut surface quality by using one factor at a time approach [6-8]. But this approach consumes more money and time for large number of experimental runs because only one factor is varied in each run, keeping all other factors constant. Also, in this approach, the interaction effects among various process parameters are not considered. To overcome such problems, Design of experiments (DOE) methods is widely used in place of one-factor-at-a time experimental approach.

Researchers [9-12] have been utilized the potential advantages of Taguchi methodology to optimize the responses with the least efforts. The effects of input process parameters on the responses are also investigated during the different processes.

In this study, two laser cut quality characteristics such as kerf taper (k_t) and surface roughness (R_a) have been optimized during pulsed Nd: YAG laser cutting of SUPERNI 718 sheet using

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Taguchi methodology. The control factors taken are: oxygen pressure, pulse width, pulse frequency and cutting speed. Based on the Taguchi quality design concept, an L_9 Orthogonal array has been used for performing the experiments and these observation results have been used for optimization. Further, analysis of variance (ANOVA) has been used to find out the most significant laser cutting parameters for optimizing the performance characteristics.

2. Experimentation using Taguchi Methodology

Taguchi methodology (TM) for robust design is a unique statistical experimental design technique which can be nullified the effect of uncontrollable factors by level combination of controllable factors or process parameters because most of the failures occur due to uncontrollable factors such as vibrations, temperature and humidity. The levels of controllable factors can be specified and controlled during experimentation. The control factors (or input process parameters) taken are the oxygen pressure (2.0 - 4.0 kg/cm^2), pulse width (0.8 - 1.0 millisecond), pulse frequency (18 - 28 Hz), and cutting speed (25 – 45 mm/min).

An exhaustive pilot experimentation has been done to decide the range of input process parameters for through quality cut. The through quality cut basically represents the dross free cutting without any burning effect as per localized visual inspection through naked eye. During the pilot experimentation, it was observed that the minimum pulse width, maximum values of pulse frequency, cutting speed and gas pressure were 0.6 ms, 30 Hz, 55 mm/min and 5.0 kg/cm^2, respectively for obtaining the complete through cut. But for the pulse width of below 0.8 ms and beyond the cutting speed of 45 mm/min and gas pressure of 4.0 kg/cm^2, the cutting was not free from dross adhesion at the bottom surface of the sheet. Therefore, keeping all these factors in mind, the level setting of input parameters has been done. The numerical values of different input parameters at different levels are shown in Table 1.

The selection of orthogonal array (OA) is based on the total degree of freedom (DOF) of the process which is calculated by using following equation [13-14]:

$$\text{DOF} = [(\text{Number of levels} - 1) \text{ for each factor} + (\text{Number of levels} - 1) \times (\text{Number of levels} - 1) \text{ for each interaction} + 1] \qquad (1)$$

In present study, four input process parameters are considered each at three levels without any interactions. Therefore, the total degree of freedom (DOF) was found as: DOF = (3-1) x 4 +1 = 9. Hence, L_9 orthogonal array has been considered for experimentation. Orthogonal arrays are a special matrix in which entries are at various levels of input parameters, and each row represents individual treatment condition [15].

Table 1: Control Factors and their Levels used in the Experiments

Symbol	Factors	Unit	Level 1	Level 2	Level 3
A	OP	kg/cm^2	2.0	3.0	4.0
B	PW	ms	0.8	0.9	1.0
C	PF	Hz	18	23	28
D	CS	mm/min	25	35	45

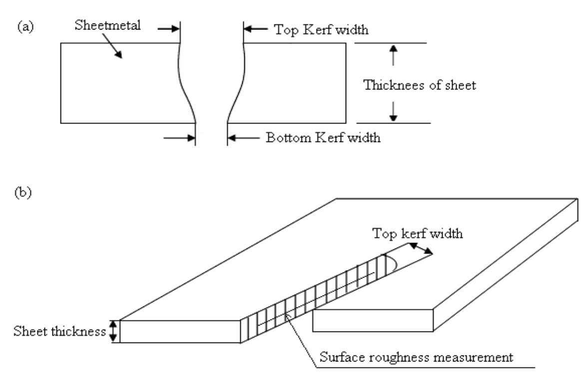

Fig. 1 Measurement of Quality Characteristics (a) For k_t value, and (b) For R_a value

In present study, 200W pulsed Nd: YAG laser beam system (SIL-200 model) has been used for the experimentation which is supplied by M/S Suresh Indu Lasers, Pune (India). The ranges of parameters with the machining system are: 0.1-20 ms for pulse width and 1-50 Hz for pulse frequency.

Oxygen was used as an assist gas. The assist gas was passing through a conical nozzle of diameter 1.0 mm and co-axially with the laser beam. The laser beam was focused using a lens of focal length 50 mm. The stand-off distance was set 1.0 mm. Nozzle diameter, focal length of lens; nozzle stand-off distance and workpiece material thickness (1.15 mm) were kept constant throughout the experimentation. The quality characteristics kerf taper (k_t) and surface roughness (R_a) are analyzed. The sampling length of each cut has been set to 28 mm. The top and bottom kerf widths (Fig. 1(a)) were measured using the Optical Measuring Microscope (Model SDM-TR-MSU, Sipcon Instrument Industries, India) at 10x magnification. The kerf widths readings taken for top and bottom kerfs are the mathematical average of five measurements of each cut taken at equal distances along the length of cut. The kerf taper angle has been computed using the following formula:

$$k_t(°) = \frac{(Top\ Kerf\ Width - Bottom\ Kerf\ Width) \times 180}{2\pi \times Sheet\ thickness} \quad (2)$$

The surface roughness (Fig. 1(b)) was measured using the Surface Roughness Tester (SURTRONIC- 25 model, Taylor Hobson Ltd, UK). All measurements were acquired using 0.8 mm cut-off length. The surface roughness readings taken are the mathematical average of three measurements of each cut.

Table 2: Experimental Observations using L_9 OA

Trials run	Factor Levels				k_t	R_a
	A	B	C	D	(°)	(µm)
1.	1	1	1	1	0.16940	3.56
2.	1	2	2	2	0.02989	3.85
3.	1	3	3	3	0.11600	3.64
4.	2	1	2	3	0.16940	3.25
5.	2	2	3	1	0.02491	3.85
6.	2	3	1	2	0.15440	3.42
7.	3	1	3	2	0.13950	3.67
8.	3	2	1	3	0.04480	2.96
9.	3	3	2	1	0.19430	3.65

3. Analysis and Discussion of Experimental Results

In Taguchi methodology, a mean standard deviation (MSD) is used to calculate the deviation between the experimental value and desired value is also known as loss function. This loss function is further transformed into a signal-to-noise (S/N) ratio. There are different MSDs available for different type of characteristics; lower is better (LB), nominal is the best (NB) and higher is better (HB) [14]. In LBC, lower kerf taper and lower surface roughness are the indication of better performance. Therefore, the LB type MSD is selected for both the quality characteristics which are computed by the following formula:

$$MSD = \left[\frac{1}{n} \sum_{i=1}^{n} y_i^2 \right] \quad (3)$$

where, y_i are the observed data (or quality characteristic) of the i^{th} trial and n is the number of replications at the same condition of experiment.

The S/N ratio for the ith performance characteristics in the jth experiment can be expressed as:

$$\eta_{ij} = -10\log_{10}(MSD_{ij}) \quad (4)$$

Table 3: S/N Ratios for Kerf Taper and Surface Roughness

Trials run	S/N ratio(dB)	
	k_t	R_a
1	15.4217	-11.029
2	30.4895	-11.71
3	18.7108	-11.222
4	15.4217	-10.238
5	32.0725	-11.71
6	16.2271	-10.681
7	17.1085	-11.2933
8	26.9744	-9.426
9	14.2305	-11.246
Overall mean (η_m)	**20.74**	**-10.95**

The calculated values of kerf taper and observed values of surface roughness from the experimental results are shown in Table 2. S/N ratios for k_t and R_a corresponding to each experimental run have been calculated by using equation (3) and (4) are shown in Table 3. The effect of each control factor at each level, on S/N ratio for k_t and R_a is shown in Table 4 and Table 5, respectively. Also, the effect of control factors on S/N ratios for k_t and R_a has been represented graphically in Fig. 2 and Fig. 3, respectively.

Table 4: Response Table for Kerf Taper

Factors	Mean S/N ratio (dB)			
	Level 1	**Level 2**	**Level 3**	**Max- min**
Oxygen pressure	21.54*	21.24	19.44	2.1
Pulse width	15.98	29.85*	16.39	13.86
Pulse frequency	19.54	20.05	22.63*	3.09
Cutting speed	20.57	21.28*	20.37	0.91

*Optimum value

Based on the analysis of S/N ratio, the optimal setting of laser cutting parameters for minimum kerf taper was obtained at level 1 (2 kg/cm^2) of oxygen pressure, level 2 (0.9 ms) of pulse width, level 3 (28 Hz) of pulse frequency and level 2 (35 mm/min) of cutting

Table 5: Response Table for Surface Roughness

Factors	Level 1	Level 2	Level 3	Max-min
Oxygen pressure	-11.32	-10.88	-10.66*	0.66
Pulse width	-10.86*	-10.95	-11.05	0.19
Pulse frequency	-10.38*	-11.06	-11.41	1.03
Cutting speed	-11.33	-11.22	-10.30*	1.03

*Optimum value

speed, i.e., $A_1B_2C_3D_2$. Similarly, the optimal cutting parameters for the surface roughness was obtained at level 3 (4 kg/cm^2) of oxygen pressure, level 1 (0.8 ms) of pulse width, level 1 (18 Hz) of pulse frequency and level 3 (45 mm/min) of cutting speed, i.e., $A_3B_1C_1D_3$.

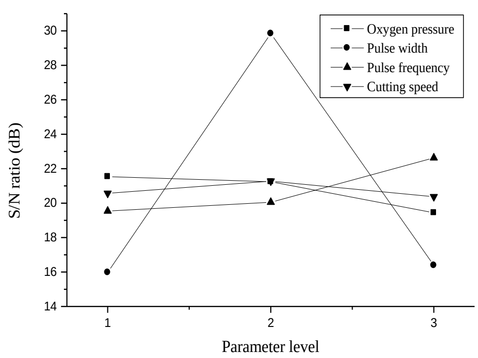

Fig. 2 Response Graph for Kerf Taper

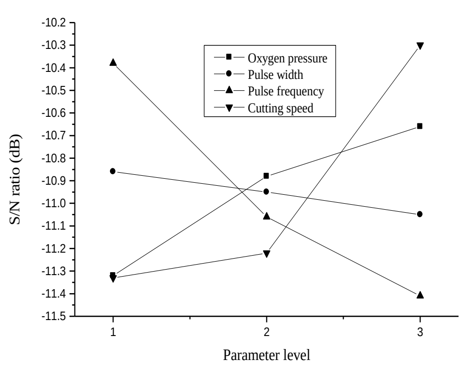

Fig. 3 Response Graph for Surface Roughness

The difference between the maximum and minimum value of the signal-to-noise ratios corresponding to each factor in Table 4 and Table 5 shows the level of significance of the controllable factors over the k_t and R_a respectively. The most effective controllable factor is the maximum of these values. In case of kerf taper, the pulse width has been found the most significant input process parameter because the difference between the maximum and minimum value of S/N ratio is maximum i.e. 13.86 for pulse width. But, in case of surface roughness, pulse frequency and cutting speed have the same value (i.e. 1.03) of difference of maximum and minimum S/N ratio. Therefore, both are the significant parameters for minimizing the surface roughness.

Table 6: Results of ANOVA based on S/N Ratios for Kerf Taper

Factor	DOF	Sum of Squars	Variance	F	Contribution (%)
OP	2	7.762#	3.881	Pooled	1.94
PW	2	373.369	186.685	81.92	93.59
PF	2	16.475	8.238	3.61	4.13
CS	2	1.353#	0.677	Pooled	0.34
Error (Pooled)	4	9.115	2.279	----	----
Total	8	398.960	------	----	100

DOF- degree of freedom; # Pooled factor, Tabulated F-ratio at 99% confidence level: $F_{0.01, 2, 4} = 18$

Table 7: Results of ANOVA based on S/N Ratios for Surface Roughness

Factor	DOF	Sum of Squars	Variance	F	Contribution (%)
OP	2	0.102025	0.051012	10.82	15.37
PW	2	0.009429#	0.004714	Pooled	1.42
PF	2	0.257593	0.128796	27.32	38.82
CS	2	0.294494	0.147247	31.24	44.38
Error (Pooled)	2	0.009429	0.004714	------	----
Total	8	0.663541	------	----	100

DOF- degree of freedom; # Pooled factor, Tabulated F-ratio at 99% confidence level: $F_{0.01, 2, 4} = 18$

A better feel for the relative effect of the different cutting parameters on the performance quality characteristics was obtained by decomposition of variance, which is called analysis of variance (ANOVA) [14]. Statistically, F-ratio provides a decision at some confidence level as to whether these estimates are significantly different. Larger F-value indicates that the variation of the process parameter makes a big change on the performance characteristics. The results of ANOVA for k_t and R_a are shown in Table 6 and Table 7, respectively. The percentage contribution of each factor for minimum kerf taper can be observed from Table 6 where pulse width contributed greatly and it has also been found that the pulse width is the most significant factor for lower k_t among all the process parameters.

According to this analysis, the significant parameters on R_a are cutting speed, pulse frequency and oxygen pressure. The percentage contributions of the cutting parameters on the R_a are shown in Table 7. According to Table 7 cutting speed is found to be the major factor affecting the R_a (44.38%). The percentage contribution of pulse frequency, oxygen pressure and pulse width on the R_a are 38.82%, 15.37% and 1.42%, respectively.

4. Confirmation Experiment

The confirmation is performed by conducting a test using a combination of the factors and levels previously evaluated. In this study, after determining the optimum condition and predicting the response under these conditions, a new experiment was designed and conducted with the optimum levels of input process parameters. The final step is to predict and verify the improvement of the performance characteristics (k_t and R_a). The predicted S/N ratio η_p using the optimal levels of the laser cutting parameters can be calculated as:

$$\eta_p = \eta_m + \sum_{i=1}^{p}\left(\bar{\eta}_i - \eta_m\right) \quad (5)$$

where η_m is the total mean of S/N ratio, $\bar{\eta}_i$ is the mean of S/N ratio at the optimal level and p is the number of input parameters.

Table 8: Results of Confirmation Experiment for Kerf Taper

	Initial cutting Parameters	Prediction	Optimum cutting parameters Experiment
Level	$A_1B_1C_1D_1$	$A_1B_2C_3D_2$	$A_1B_2C_3D_2$
Kerf taper (°)	0.16940	----	0.0847
S/N ratio (dB)	15.4217	33.080	21.44

Improvement in S/N ratio = 6.0183 dB

Table 9: Results of Confirmation Experiment for Surface Roughness

	Initial cutting Parameters	Optimum cutting parameters	
		Prediction	Experiment
Level	$A_1B_1C_1D_1$	$A_3B_1C_1D_3$	$A_3B_1C_1D_3$
Surface roughness (μm)	3.56	----	2.86
S/N ratio (dB)	-11.029	-9.35	-9.13

Improvement in S/N ratio = 1.899 dB

The results of confirmation experiment using optimal cutting parameters are shown in Table 8 and Table 9. Table 8 shows the improvement in the S/N ratio of kerf taper from the starting cutting parameters to the level of optimal cutting parameters is 6.0183 dB. The kerf taper is decreased by 2.0 times. So, the taper is greatly improved by using the approach. Table 9 shows the improvement in the S/N ratio of R_a from the starting cutting parameters to the level of optimal cutting parameters is 1.899 dB. The surface roughness is decreased by 1.24 times. The experimental results confirmed the validity of the used Taguchi method for enhancing the cutting performance.

5. Conclusions

In the present study, Taguchi methodology has been used for optimization of kerf taper and surface roughness separately during Nd: YAG laser cutting of nickel based super alloy thin sheet. The following conclusions have been made from the present work:

i. As compared to initial parameter setting the S/N ratio for kerf taper and surface roughness is improved in the operating range by 6.0183 dB and 1.899 dB, respectively.

ii. The optimum value of input process parameter for minimum kerf taper is: oxygen pressure – 2 kg/cm^2, pulse width - 0.9 ms, pulse frequency – 28 Hz and cutting speed – 35 mm/min. And for minimum surface roughness is: oxygen pressure – 4 kg/cm^2, pulse width - 0.8 ms, pulse frequency – 18 Hz and cutting speed – 45 mm/min.

iii. The most significant factor for kerf taper is pulse width (93.6% contribution) while other factors have very little or no significant effect in their range. For the surface roughness cutting speed is found to be most significant process parameter followed by pulse frequency and oxygen pressure. The pulse width has no significant effect on the surface roughness with in the specified range.

iv. The confirmation test indicates that the performance characteristics can be improved by using the proposed statistical technique.

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