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Prediction of Optimum Parameters in the Laser Cutting of Titanium Alloy Sheet

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Abstract

With the development of large varieties of advanced materials, it has become necessary to develop the different machining methods to machine these materials with satisfactory quality. These materials have wide applications in technologically advanced industries and these applications require very precise and complex shapes that may not be obtained by the conventional cutting methods. To fulfil these objectives, another class of machining processes called advanced machining processes may be used. In this study, the experiments have been conducted by using well planned design of experiments based L_{27} orthogonal array. The experimental data have been used to develop the second order regression models of kerf width (KW), kerf deviation (KD), and kerf taper (KT). In order to find the suitability and predictability of the developed models, statistical analysis has been used. The analysis shows that the developed models may be used to predict the respective quality characteristics in certain regimes. The optimum predicted results have been validated by conducting the validation experiments at optimum parameters setting. The validation results have been found in very good agreement with the predicted results.

Keywords

Laser cutting, Titanium alloy sheet, Modelling, Optimization, Statistical analysis

Introduction

It is not easy to cut Titanium alloys properly using conventional cutting methods due to advanced properties like high strength-weight ratio, good corrosion resistance, fatigue resistance, high stiffness, and quality to sustain at medium-high temperatures showing no creep. Titanium and its alloys have bad thermal conductivity thus generated machining heat cannot be dissipated properly which results melting of tool tip at high interface temperature. This alloy has high chemical reaction ability and low elastic modulus, thus chemical reaction of tool with work piece at elevated temperature takes place and minimizes the tool life [1]. The ability of laser to cut depends mainly on the optical properties and thermal properties of the working materials, but it is independent from mechanical and physical properties of materials. These alloys are widely used in industries for different manufacturing applications like airframe components, chemical processing industries, cryogenic vessels, heat exchangers, automobiles, and medical equipment's. Laser beam machining is a non-traditional process and uses thermal energy for machining. Both macro and micro machining of difficult to cut and advanced materials such as super alloys, hardened steel, composites, and ceramics is done by using laser beam [2].

There is a need for investigation and optimization of the different process parameters to improve the quality characteristics. Most of the studies are based on one process parameter varied at a time, which requires a large number of experiments to run. This is because only one factor is varied, and remaining factors are taken constantly. To solve this problem, researchers use the DOE (design of experiments) methodologies such as the response surface methodology, Factorial design, Taguchi methodology. These DOE techniques can be used for single as well as multi-objective optimization. For precision cutting and intricate profile cutting, the use of Nd:YAG laser is growing. Due to the shorter wavelength, the reflectivity is lesser and absorbing quality is higher by metallic surfaces thus it enables to cut the highly reflective materials [3]. The procedure followed is melting, vaporization, and chemical degradation to material removal by laser machining. Assisted gas is used to remove the liquefied material from the machining area. It is superior in comparison to other cutting methods because there is material versatility, flexibility in production, higher accuracy with edge quality, and hybridization ability [3, 4].

Nd:YAG laser has some specifications as solid state laser, optically pumps the energy, workable wavelength of 1.06 μm, low mean power in continuous mode, pulsed mode gives high peak power, little heat affected zone, and KWs. CO_2 laser specification are as gaseous laser, use electrical pumping source, workable wavelength 10.6 μm, and high mean power [5]. Due to favorable cost and availability, air is being used as assisted gas. Nitrogen and Argon as assisted gasses gives more satisfactory results than air [6]. Pandey and Dubey, air as assisted gas is replaced by oxygen which can reduce more the KD at both sides as comparison to air [7].

Thus, due to all the difficulties there is a need for suitable cutting process for Titanium and its alloys. Laser beam machining is one of the advanced machining processes like electrical discharge machining, electron beam machining, laser beam machining, and ultrasonic machining. There is a need for proper optimization methodology to do the optimization of the process parameters [8]. A schematic diagram of laser cutting is shown in figure 1.

The study of Nd:YAG laser cutting of austenitic stainless steel sheet of 1.2 mm thickness to check the effect of process

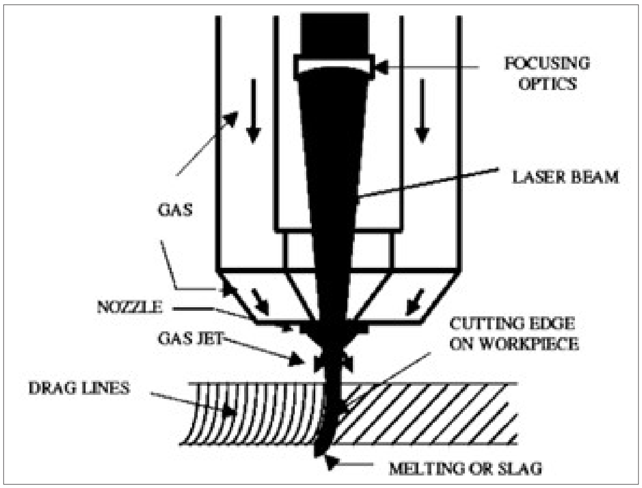

Figure 1: Schematic of cutting process by laser beam [8].

parameters on quality characteristics like KW found that frequency and cutting speed shows positive effect while power and gas pressure shows negative effect [9]. While in the cutting of 4130 steel by taking CO_2 laser system it was found that power shows major effect, feed rate shows moderate effect on KW [10].

A study on Al7075 sheet of 2 mm thickness in laser micro-machining by Nd:YVO_4 pulsed laser having low power capability of 9.4 watts is done. Taguchi methodology with L_9 OA is applied and the results of experiment are then verified by the ANOVA (analysis of variance) and then confirmation test. Responses are as the KW, HAZ and SR (surface roughness) increased with increasing power and frequency while decreased with increasing scanning speed. SR decreases with increasing frequency after particular point and found that the KW and other qualities as HAZ, SR are increased with laser power and frequency while decreased with scanning speed [11]. Shorter pulse duration in Nd:YAG laser cutting gives lower KT. In the cutting of Hastelloy-X sheet 1 mm, parametric regime is based on key parameters pulse energy and cutting speed, was established through experiment. Hastelloy-X percentage composition as 47.2 nickel, 21.0 chromium, 18.5 iron, and 9.0 molybdenum in major [12].

The CFRP composite of 3 mm thickness is cut with a high-quality CO_2 slab laser of 3.5 kW. The quality characteristics KW, degree of delamination, HAZ, and perpendicularity of cut kerf, are reduced by selecting the optimum of process parameters. The use of coaxial subsonic and off-axial supersonic assisted gas jets leads to minimizing the HAZ [13]. Al-Sulaiman et al. studied CO_2 laser cutting of composite of carbon/carbon fibers consisting of 64 layers with orientation of 0°. The effect on KW size according to different laser power is examined; found that the KW is increasing with increasing the power. The orientations of fiber axis normal to the direction of work-piece motion results larger KW by the effect of thermal conductivity [14]. The effects of varying process parameters on hole quality are examined by Tuersley et al. using a pulsed Nd:YAG laser to machine glass matrix composite comprising SiC fibers in a borosilicate glass matrix. There is optimization for the pressure of assisted gas, focal point of beam in respect of surface and maximum cutting speed variation with the sheet thickness [15].

The alternative to the regression technique failure is artificial intelligence-based techniques, by using the artificial neural networks to provide an adequate model. To precisely describe the complex non-linear relationship between control factors and quality characteristics, the regression models are not suitable, so these advanced techniques become useful in manufacturing sector. Shrivastava and Pandey, used the hybrid approach of genetic algorithm and multiple regression analysis to optimize the cutting parameters during laser cutting of Inconel-718 sheet [16]. Some other researchers have also applied the hybrid approach of design of experiments-based techniques and artificial intelligence-based techniques. They have observed considerable improvements in different quality characteristics by using these methods [17-20].

DOE Methodology for Parameters Design

There is a need for investigation of different optimizing process parameters to improve the quality of the cutting process. Large experimental activities are dependent on single parameter change at a time thus it requires a greater number of experiments. To minimize the number of experiments the DOE methodology-based Taguchi robust parameters design method is used for experimental study [8].

Designs for experimentation

Taguchi methodology is a robust parameter design technique to improve manufacturing productivity. It is a simple, systematic, and off-line statistical process parameter design technique to reduce the number of experiments required. Taguchi Methodology explains that "The effect of uncontrollable factors can be nullified by appropriate selection of level combinations of controllable factors or process parameters" [21]. There is the effect of both controllable and uncontrollable factors on output manufacturing process parameters. Thus, the effect of uncontrollable factors (humidity, noise, vibrations, etc.) on process parameters can be removed or minimized by choosing the right input parameter levels. The designed matrixes for experimentation generally known as orthogonal array (OA) is based on control factors and their levels tabulated in Taguchi method [22]. Equation 1 is the mathematical formula to calculate the degree of freedom.

$$dof = [(counting\ of\ levels - 1)\ for\ each\ control\ factor + 1] \quad (1)$$

Degree of freedom (dof) explains the orthogonal array size, its size should be greater than or equal to the dof. To improve resolution accuracy OA size is taken larger than the dof [22], thus L_{27} OA is taken to design of experimentation. The mathematical way of representing cost as a function of product variation is quality loss function also known as mean square deviation (MsD) from the desired value. Following are the types of quality loss function or MsD based on the nature of quality characteristics.

For smaller the better type (Sb-type)

$$MsD = \left[\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right] \quad (2)$$

For higher the better type (Hb-type)

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

For nominal the better type (Nb-type)

$$MsD = \left[\frac{1}{n}\sum_{i=1}^{n} (Y_i - M)^2\right] \quad (4)$$

Where, y_i is the observed response or quality value at i^{th} trial or experimental run and n is the number of trials at same parameter level.

In Taguchi method, the signal-to-noise (S/N) ratio (ὴ) represents the quality characteristics for responses or observed data. The word 'signal' represents the desirable value, word 'noise' represents the undesirable values and scatter around the desired values is expressed by ratio of these two. When the proportion of desired values becomes larger than the undesired values, the S/N ratio will be greater and then scatter will be lower. For all types of quality characteristics (Sb, Hb, and Nb-types), S/N ratio is calculated using equation 5.

$$\eta = -10\log_{10}(MsD) \quad (5)$$

Where, MsD is mean square deviation from desired values.

It is desired to maximize the S/N ratio always whatever may be the nature of quality characteristics (Sb-type, Hb-type, etc.) because the minimum scatter can be achieve from larger S/N ratio. The maximum value of mean or average S/N ratio at a particular level shows the optimum level of a control factor. To check the relative effect of different process parameters or control factors, ANOVA is applied.

Experimental work strategy

In this research work parametric optimization in laser cutting of Titanium alloy sheet has been done. It has been already discussed the properties, applications of Titanium and its alloys. In this study, Titanium_alloy_grade-II sheets 1.5 mm thick having chemical composition (by % of weight Nitrogen, Carbon, Oxygen, Hydrogen, Iron and Titanium are 0.015, 0.022, 0.101,0.001, 0.118 and 99.39, respectively). Since these alloys have high cost, it is required to minimize the wastage of material using proper cutting methods. In comparison to inert gasses air gives poor cut qualities but cost is much below than inert gases. Input parameters or control factors gas pressure, pulse width, pulse frequency, and cutting speed are taken, whereas the out-put parameters or quality-characteristics are KW at top, KD at top and KT. Pulsed Nd:YAG solid state laser machining system is utilized for the experimental purpose. The machine specifications are as mean power 250 watts, CNC controlled operating mechanism, 240-A fixed current, assisted by compressed Air, 600 µm spot diameter and 1.5 mm tip distance for nozzle, collimation lenses with 40 mm focal length and sheet metal dimension of 20.0 x 10.0 x 0.15 (cm^3), optical Microscope (4X- zoom Leica SAPO).

The selection and designing of process parameters based on three levels of each processing parameters assuming no interaction effect among the different parameters is taken. A pilot experiment is done to decide the range of process parameters or control factors for through cutting of workpiece sheet. The control factors and levels are shown in table 1.

The dof for three levels and four control factors is obtained as [(3-1) x 4+1] = 9. But to achieve higher resolution L27 (OA) is selected for this experimentation. The straight cuts of about 20 mm are made, KWs are measured at different

Table 1: Control factors values at three levels.

Symbol	Factors	Units	Level 1	Level 2	Level 3
A	Assisted gas pressure	Kg/cm^2	5.0	7.0	9.0
B	Pulse width	ms	2.0	3.0	4.0
C	Pulse frequency	Hz	12	14	16
D	Cutting speed	mm/min	10	20	30

places along the length of cut on the top side. Arithmetic average of values which gives kerf width at top (TKW) and KD is measured by taking difference between the maximum and minimum values of TKW. The values of quality characteristics KW (mm), KD (mm), KT in degrees for 27 experiments are shown by graph in figure 2.

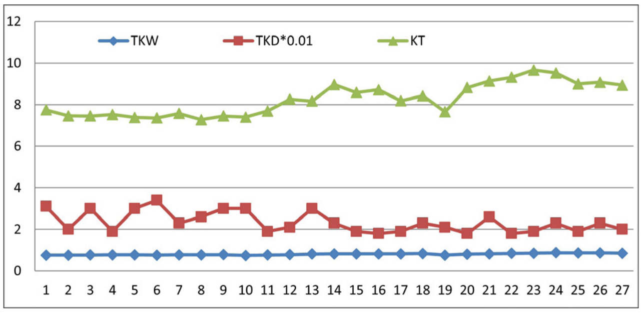

Figure 2: Experimental values.

Regression models and validation

Response models

A second order regression models for responses TKW, TKD (top kerf deviation), and KT are developed by regression analysis. The interactions effects between different process parameters or control factors are analyzed to know about responses [23]. Upon taking the experimental output values of quality characteristics, the coefficients for second order regression models have been obtained using MINITAB software. The uncoded units (actual experimental values) are taken for regression analysis. The final models for the TKW, TKD, and KT are given in the form of regression equations as following:

$$TKW = 0.454 - 0.01749Y_1 + 0.173Y_2 + 0.0176Y_3 - 0.00900Y_4 + 0.00037Y_1^2 - 0.0181\ Y_2^2 - 0.00059Y_3^2 - 0.000011Y_4^2 + 0.00422Y_1 * Y_2 - 0.00571Y_2 * Y_3 + 0.000568Y_3 * Y_4 - 0.000027Y_1 * Y_4 + 0.00128Y_1 * Y_3 + 0.000545\ Y_2 * Y_4 \quad (6)$$

S = 0.0124540 R-sq = 95.7% R-sq (adj) = 90.8%

$$TKD = 0.367 + 0.0137Y_1 - 0.0004Y_2 - 0.0485Y_3 - 0.00524Y_4 + 0.000295Y_1^2 - 0.00554Y_2^2 + 0.00179Y_3^2 + 0.000073Y_4^2 - 0.000133Y_1 * Y_2 + 0.00230Y_2 * Y_3 + 0.000084Y_3 * Y_4 + 0.000098Y_1 * Y_4 - 0.00151Y_1 * Y_3 + 0.000189Y_2 * Y_4 \quad (7)$$

S = 0.00369676 R-sq = 92.2% R-sq (adj) = 83.0%

$$KT = 15.0 - 0.340Y_1 + 1.49Y_2 - 0.857Y_3 - 0.297Y_4 - 0.0224Y_1^2 - 0.279Y_2^2 + 0.0122Y_3^2 + 0.00031Y_4^2 + 0.0939Y_1 * Y_2 - 0.0678Y_2 * Y_3 + 0.0155\ Y_3 * Y_4 - 0.00337Y_1 * Y_4 + 0.0597Y_1 * Y_3 + 0.0257Y_2 * Y_4 \quad (8)$$

S = 0.251817 R-sq = 95.6% R-sq (adj) = 90.4%

Where, Y_1 = gas pressure (A), Y_2 = pulse width (B), Y_3 = pulse frequency (C), Y_4 = cutting speed (D), R-sq = R-square, and R-sq (adj) = adjusted R-square.

Model validation

The S-values, R^2-values and adjusted R^2-values are being calculated for models of TKW, TKD, and KT to know about fitting of data using regression models. The correlation coefficients (R-values) for respective characteristics are 0.978, 0.960, 0.977, respectively, which are accepted as greater than confidence level, hence the data predicted by regression models are well fitted [23]. The ANOVA shown in table 2 has been carried out to check the adequacy of the regression models [24]. The p-values of all regression models are lower than 0.01 or 99% confidence level than it can be conclude that the developed regression models are significant and adequate for all the responses [24].

Table 2: ANOVA result.

Source	DF	SS	MS	f-value	p-value
TKW					
Regression	14	0.0419074	0.0029934	19.30	0.000
Residual Error	12	0.0018612	0.0001551	-	-
Total	26	0.0437686	-	-	-
TKD					
Regression	14	0.00192679	0.00013763	10.07	0.000
Residual Error	12	0.00016399	0.00001367	-	-
Total	26	0.00209079	-	-	-
KT					
Regression	14	16.3592	1.1685	18.43	0.000
Residual Error	12	0.7609	0.0634	-	-
Total	26	17.1201	-	-	-

Note: DF = degree of freedom, SS = sum of squares, and MS = mean of squares.

Results and Analysis for Parametric optimization

The optimization of single quality characteristics vs the process parameters using Taguchi methodology is done as follows. Here the influence of process parameters on single

Table 3: Response table of mean of S/N ratio for top kerf width (TKW).

Level	A	B	C	D
1	**2.301**	**2.259**	**2.025**	**1.943**
2	1.927	1.801	1.926	1.913
3	1.569	1.737	1.845	1.940
Delta	0.732	0.522	0.180	0.030
Rank	1	2	3	4

quality characteristics to improve the quality has been checked. The mean of S/N ratio for TKW vs the parameters is shown by table 3, the mean of S/N ratio for TKD vs process parameters is shown by table 4, and the mean of S/N ratio for KT vs process parameters is shown by table 5.

From all observations it is concluded that the highest value of S/N ratio for respective process parameter represents the optimum parametric condition. The optimum parametric condition for TKW is that assisted gas pressure of 5 Kg/cm^2, pulse width of 2 ms, pulse frequency of 12 Hz, cutting speed of 10 mm/min. The optimal values setting for TKD is $A_3B_3C_2D_2$ which is assisted gas pressure of 9 Kg/cm^2, pulse width of 4 ms, pulse frequency of 14 Hz, cutting speed of 20 mm/min. The optimum parameter values for KT are assisted gas pressure at 5 Kg/cm^2, pulse width 2 ms, pulse frequency at 12 Hz and cutting speed at 30 mm/min which is $A_1B_1C_1D_3$. Delta is the difference between highest and lowest S/N ratio values of particular parameter within three levels, which decides the rank or contribution of process parameters.

Table 4: Response table of mean of S/N ratio for top kerf deviation (TKD).

Level	A	B	C	D
1	31.53	32.58	32.89	32.91
2	33.13	32.67	**33.32**	**33.19**
3	**33.71**	**33.13**	32.16	32.27
Delta	2.18	0.55	1.15	0.92
Rank	1	4	2	3

Table 5: Response table of mean of S/N ratio for kerf taper (KT).

Level	A	B	C	D
1	**-17.47**	**-17.99**	**-18.16**	-18.43
2	-18.33	-18.54	-18.32	-18.30
3	-19.08	-18.34	-18.40	**-18.14**
Delta	1.61	0.55	0.23	0.29
Rank	1	2	4	3

Confirmation experiment

To check the improvement at optimized parameters levels an experimental test is done which is given in table 6. These optimal levels of control factors or process parameters are obtained by applying Taguchi methodology. An improvement in S/N ratios for quality characteristics at optimal levels of process parameters. The comparison between magnified/microscopic photographs of laser cut geometrical qualities at minimum parameters setting and optimal setting is shown in

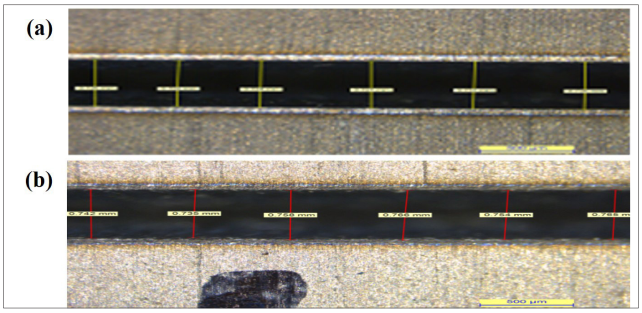

Figure 3: Scanned view of laser cut top kerf width at **(a)** initial parameters setting and **(b)** optimal parameter setting.

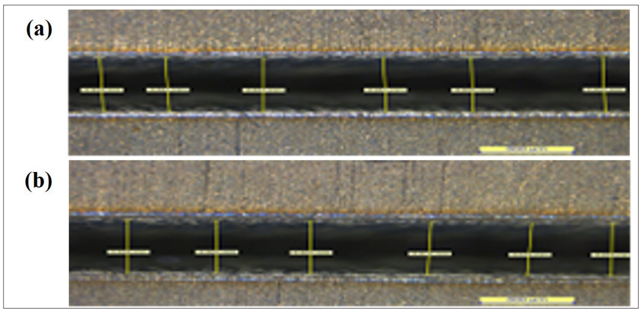

Figure 4: Scanned view of laser cut top kerf deviation at **(a)** initial parameters setting and **(b)** optimal parameter setting.

Table 6: Confirmation experiments for quality characteristics.

Initial cutting parameter	Setting for minimum value	Optimum parameters for laser cutting	
		Prediction	Experiment
TKW			
Level	$A_2B_1C_1D_2$	$A_1B_1C_1D_1$	$A_1B_1C_1D_1$
Top kerf width (mm)	0.7436	0.73016	0.73202
S/N ratio (dB)	2.5732	2.73168	2.70954
Error prediction-in S/N ratio (dB)	-	-0.02214	-
TKD			
Level	$A_3B_2C_1D_1$	$A_3B_3C_2D_2$	$A_3B_3C_2D_2$
Top kerf deviation (mm)	0.0180	0.01783	0.01764
S/N ratio (dB)	34.8645	34.9754	35.07003
Error prediction-in S/N ratio (dB)	-	0.09463	-
KT			
Level	$A_1B_3C_2D_1$	$A_1B_1C_1D_3$	$A_1B_1C_1D_3$
kerf taper (mm)	7.2766	6.99093	7.07136
S/N ratio (dB)	-17.2385	-16.8907	-16.99006
Error prediction-in S/N ratio (dB)	-	-0.09936	-

figure 3 and figure 4.

Conclusion

The experimental study on the laser cutting of Titanium alloy sheet has been conducted successfully. The main conclusions of the study are as below:

- The developed regression models for KW, KD, and KT have been found to be reliable and adequate for predicting quality values above 90% confidence level.
- The statistical analysis results show that the regression models of double order for KW, KD and KT have been found reliable and adequate as correlation coefficients for all these models are 0.978, 0.960 and 0.977, respectively.
- At optimal parametric levels, the improved S/N ratio and quality values have been observed. The comparison results show certain improvements in different quality characteristics at optimum setting against the minimum value settings.
- The KW, KD and KT are reduced from 0.7436 mm to 0.73202 mm, 0.0180 mm to 0.01764 mm and 7.2766° to 7.07136° respectively at the optimum parameter settings.

Acknowledgements

None.

Conflict of Interest

The authors declare no conflict of interests that are relevant to the content of this article.

Credit Author Statement

Tarun Singh: Methodology, Experimentation, Formal analysis, Writing - original draft preparation; Vijay Verma: Writing - review and editing; Arun Kumar Pandey: Writing - review and editing, Supervision. All the authors read and approved the manuscript.

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