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Optimization Of Edge Quality During CO_2 Laser Cutting Of Titanium Alloy

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Abstract— Titanium Grade 5 material has high demand in different industries due to their superior properties. The conventional cutting methods face difficulties for cutting these alloys due to their poor thermal conductivity, low elastic modulus and high chemical affinity at elevated temperatures. Laser cutting may be used for quality cuts by proper control of different process parameters. The aim of present research is to simultaneously optimize kerf taper and surface roughness in the CO_2 laser cutting of Titanium grade 5 (Ti-6Al- 4V) sheet. The paper presents optimal solutions and improvements in different quality characteristics thereof. The significant control factors have been found with further discussion of their effect on two important quality characteristics kerf taper and surface roughness.

Keywords— Optimization of Laser cutting, Titanium Alloycutting

I. INTRODUCTION

Titanium Grade 5 (Ti-6Al- 4V) material is most widely used for different industries such as aerospace, marine, chemical, food processing and medical due to their properties such as high strength and stiffness at elevated temperatures, high strength to weight ratio, high corrosion resistance, fatigue resistance, and ability to withstand high temperatures without creeping[1]. Titanium Grade 5 cannot be cut easily by conventional cutting methods due to their improved mechanical properties, poor thermal conductivity, low elastic modulus and high chemical affinity at elevated temperatures. Due to the poor thermal conductivity of these alloys, the heat generated during the cutting cannot dissipated properly which results very high temperature at the tool work piece inter face and melting of the tool tip. Thus adversely affects the tool life. Ti is chemically reactive at elevated temperatures due to which the tool material either rapidly dissolves or chemically reacts during the cutting process, resulting premature tool life [2]. The low elastic modulus of Ti Grade 5 permits greater deflection of work piece during machining and complexity of the machining increases. While machining the Ti Grade 5, the contact length between the tool and chip has been found very small due to which high cutting temperatures and high cutting stresses are concentrated near the tool tip which results the melting of tool tip and finally tool life reduces. Thus there is a crucial need for reliable and effective cutting process for Ti-6Al- 4V. Alternatively for the cutting of these materials advanced cutting processes such as Electric discharge machining, ultrasonic machining, laser beam machining may be used with some limitations. But for using these advanced cutting methods, a lot of research work has been required so that the required objectives may be fulfilled by control- ling different process parameters.

Laser cutting is one of the non conventional cutting processes, most widely used for generating complex shapes and different geometries with narrow kerf in almost all categories of materials such as metals, nonmetals, ceramics and composites. The cutting capability of laser mainly depends upon the thermal and optical properties of the material rather than the mechanical properties [3]. The material to be cut is locally melted by the focused laser beam. The melt is then blown away with the aid of assist gas, which flow coaxially with the laser beam, forming a kerf. In metal cutting procedures, different types of assist gases are used such as oxygen and nitrogen. The selection of an appropriate gas type or a mixture of gases with a given mixing percentage is fundamental to minimize the cutting cost by increasing the cutting speed. In order to obtain the desirable high level of cutting edge quality it is important to choose the optimal combinations of the process parameters as these parameters have an effect on the output characteristics or quality features namely: upper kerf, lower kerf and cutting edge roughness, etc.

In the last few years, there has been growing interest in the use of CO_2 lasers for precision cutting of thin sheet- metals and for these applications that demands narrow kerf widths, small HAZ and intricate cut profiles. Most of the researchers have varied one parameter at a time to investigate the effect of different parameters such as laser power, pulse width, pulse frequency, cutting speed, type and pressure of assist gas on the different output characteristics for the different category of materials such as metals, nonmetals, composites and ceramics [4–7]. This type of method requires large number of experiments because only one process parameter is varied at a time. To overcome this problem, different researchers have used design of experiment (DOE) methods such as robust parameter design method, response surface methodology and factorial design. But such types of studies are mainly focused for single objective optimization. Some of researchers have used these methods for multi-objective optimization of different quality characteristics in interest [8–10]. Few researchers have studied the laser cutting performance of Ti alloys in different conditions. When these alloys are cut with oxygen assist gas, at even low pressure, the uncontrolled burning of cutting front starts that results wide kerf and poor surface quality. For air assisted laser cutting, the reaction of Titanium with oxygen and nitrogen produces a thin layer of hard and brittle oxides and nitrides, and generates much thicker HAZ in comparison to that of nitrogen or argon [11]. In order to overcome these problems the Titanium alloys may be cut by using inert gases such as argon and helium.Raoetal.[12] have used nitrogen(N2), argon(Ar) and helium(He) for the pulsed laser cutting of 1mm pure Titanium sheet. They found straight and parallel cuts with Ar and N2 assist gases while use of He gave wavy cut surface. Almeidaetal. [13]. the laser cutting process is highly uncertain and unpredictable and it depends on number of input process parameters used for the cutting. The relationship between input and output parameters is nonlinear and complicated.

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The conventional methods of modeling and optimization require large amount of experimental data which has been found costly and time consuming. To overcome these difficulties, Artificial Intelligence (AI) based modeling and optimization techniques such as artificial neural network (ANN), fuzzy logic (FL) and genetic algorithm (GA), are used. GA is one of the powerful optimization method may be employed for the optimization of various processes. GA has the advantages of finding the global optimum point and on the other hand does not have the limitations of gradient method i.e., concavity, continuity, and derivability of the target function [14]. This method can be employed for the optimization of linear as well as nonlinear problems. These techniques have been used for the modeling and optimization of different advanced machining processes [15–18], but very limited applications have been reported in the laser cutting of different materials [19–21].

The present paper reports the multi-objective optimization of cut qualities in the CO_2 laser cutting of Titanium alloy sheet. The motivation for the investigation is the fact that Titanium alloys being increasingly used in different industries and engineers of these industries are trying to obtain best qualities of these materials in the laser cutting. In this investigation, Ti-6Al-4V (Titanium alloy sheet grade 5) sheet has been selected because it is known for its exceptional performance characteristics and is one of the mostly used Titanium alloys. Due to higher material costs, the Ti alloys require such type of cutting methods in which minimum wastage of materials is obtained with satisfactory cut qualities. Laser cutting has cap-ability to generate narrow kerfs but the reported research works show that poor cut qualities are obtained by use of air or nitrogen assist gases due to low thermal conductivity and high chemical reactivity at elevated temperatures. The use of costlier inert gases may further increase the cutting cost. Therefore, the aim of present research is to obtain good quality of cut by using N2 as assist gas. Regression analysis has been applied for the modeling of kerf taper and cut edge surface roughness with the help of data obtained by the L27 orthogonal array experimentation. The developed second order regression models for kerf taper and surface roughness have been used as objective functions in GA based multi-objective optimization of these quality characteristics. The effects of significant factors for kerf taper as well as surface roughness have also been discussed. Also ANOVA has been conducted for finding the percentage of contribution.

II. EXPERIMENTATION

A. Design of experiments

The total number of experiments can be substantially reduced with the help of a well designed experimental plan without affecting the accuracy during the experimental study of any manufacturing process. Taguchi have suggested that it is better to make the process robust rather than equipments and machinery just by nullifying the effects of variations through selection of appropriate parameter level. Taguchi has suggested properly designed experimental matrices known as orthogonal arrays (OAs) to conducts the experiments. In this present research work four control factors with three levels of each have been considered. Hence experiments can be performed by using simplest L9 OA. But authors have selected L27 OA for high resolution factor [22].

B. Experimental Details

The experiments have been performed on 5000W CO_2 laser cutting system. The assist gas used is Nitrogen and it is passed through a nozzle of 1 mm diameter, which remains constant throughout the experiments. The laser frequency is 8500Hz. The Titanium alloy sheet (Ti-6Al-4V) of thickness 2 mm is used as work material. The chemical compositions of the Ti-6Al-4V are shown in Table 1. Assist gas pressure, pulse width or pulse duration, pulse frequency and cutting speed have been selected as input process parameters (control factors).

Table 1

Chemical composition of titanium alloy sheet (grade-5).

Al	Fe	Sn	V	Ti
6.22%	0.19%	0.56%	3.35%	89.60%

An exhaustive pilot experimentation has been performed in order to decide the range of each control factors for complete through cutting. The different control factors and their levels are shown in Table 2.

Table 2

Control Factors and their levels used in experiments

CONTROL FACTORS FOR KERF TAPER AND SURFACE ROUGHNESS					
Symbol	Parameters	Unit	Level 1	Level 2	Level 3
A	Gas Pressure	Bar	10	15	20
B	Cutting Speed	m/min	1.5	3	4.5
C	Laser Power	Watts	1500	3000	4500
D	Focal Point Position	mm	-1	0	1

With the help of surface roughness supplied by Mitutoyo, Japan. The average of all three Ra values, represent the SR for an experimental run. The KT has been calculated by using following formula,

$$KT(^0) = \frac{(\text{TopKerfwidth-BottomKerfwidth})*180}{2\pi t}$$

Where, t is the thickness of the sheet metal.

The experimental measured values of different quality characteristics such as SR and KT are shown in Table 3.

Table 3

Experimental Measured Values of KT & SR

Exp. No.	Factor Level				SR (μm)	KT (°)
	A	B	C	D		
1	10	1.5	1500	-1	9.41	2.006
2	10	1.5	3000	0	9.07	1.275
3	10	1.5	4500	1	9.9	0.831
4	10	3	1500	0	9.56	1.232
5	10	3	3000	1	9.6	2.035
6	10	3	4500	-1	10.1	0.473
7	10	4.5	1500	1	10.6	1.705
8	10	4.5	3000	-1	11.2	1.605
9	10	4.5	4500	0	12.5	0.430
10	15	1.5	1500	0	5.5	2.135
11	15	1.5	3000	1	6.8	1.175
12	15	1.5	4500	-1	10.35	1.404
13	15	3	1500	1	8.9	2.565
14	15	3	3000	-1	9.1	1.748
15	15	3	4500	0	11.18	0.330
16	15	4.5	1500	-1	8.9	2.938
17	15	4.5	3000	0	7.8	1.419
18	15	4.5	4500	1	11.96	1.075
19	20	1.5	1500	1	6.89	2.866
20	20	1.5	3000	-1	5.73	3.912
21	20	1.5	4500	0	9.1	2.006
22	20	3	1500	-1	9.28	3.568
23	20	3	3000	0	8.89	2.365
24	20	3	4500	1	11.46	1.404
25	20	4.5	1500	0	9.5	2.795
26	20	4.5	3000	1	10.8	2.322
27	20	4.5	4500	-1	12.3	2.408

C. Analysis of Variance

Statistical analysis of variance (ANOVA) is done to investigate which design parameter significantly affects the SR and KT for CO2 Laser Cutting of Ti Grade 5 material. Based on the ANOVA, the relative importance of the cutting parameters with respect to SR and KT was investigated to determine the optimum combination of the turning parameters. All analysis is carried out for a significance level of α=0.05, i.e., for confidence level of 95%. ANOVA table also has probability level that is the realized significance level, associated with the F-tests for each source of variation. The sources with a probability level less than 0.05 are considered to have a statistically significant contribution to the performance measures. Also the percentage of contribution of each source to the total variation indicates the degree of influence on the result by each source.

Taguchi's method of analyzing means of the S/N ratio using conceptual approach involves graphical method for studying the effects and visually identifying the factors that appear to be significant. The rank indicates the dominant machining parameter.

SURFACE ROUGHNESS

The desired characteristic for surface roughness is lower the better.

$$S/N = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}(y_i^{\,2})\right]$$

Table 4: ANOVA Table for SR

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Gas Pressure	2	8.558	8.558	4.279	3.77	0.043
Cutting Speed	2	30.0963	30.0963	15.0481	3.26	0
Laser Power	2	26.1004	26.1004	13.0502	11.5	0.001
Focal Point Position	2	0.9593	0.9593	0.4797	0.42	0.662
Resiual Error	18	20.4281	20.4281	1.1349		
Total	26	86.1422				

Analysis of variance is a method of portioning variability into identifiable sources of variation and the associated degree of freedom in an experiment. The frequency test (F-test) is utilized in statistics to analyze the significant effects of the parameters, which form the quality characteristics. Table 4 shows the result of ANOVA analysis of S/N ratio for surface roughness. This analysis was carried out for a level of significance of 5%, i.e., for 95% a level of confidence. The last column of the table shows the "percent" contribution (P) of each factor as the total variation, indicating its influence on the result. The contribution of each variable as,

The percentage of contribution of GP is 9.93%

The percentage of contribution of CS is 34.84%

The percentage of contribution of LP is 30.29%

The percentage of contribution of FP is 23.71%

The effect of process parameters on the surface roughness values was shown in Fig. 1. The SR increases with increasing in Gas Pressure but after 15 bar it's slowly reducing, but in case of SR is reducing when increasing the Cutting speed. The SR is drastically reducing with increase in Laser Power. In case of Focal point, there is no much difference.

In this case, the most significant factor that has an effect on strength is Cutting Speed followed by Laser Power and Gas Pressure.

Based on the ANOVA results in Table 5 the percentage contribution of various factors to surface roughness is identifiable. Here, Cutting Speed is the most influencing factor followed by Laser Power. The percentage contribution of speed and Laser Power towards surface roughness is 34.84% and 30.29% respectively.

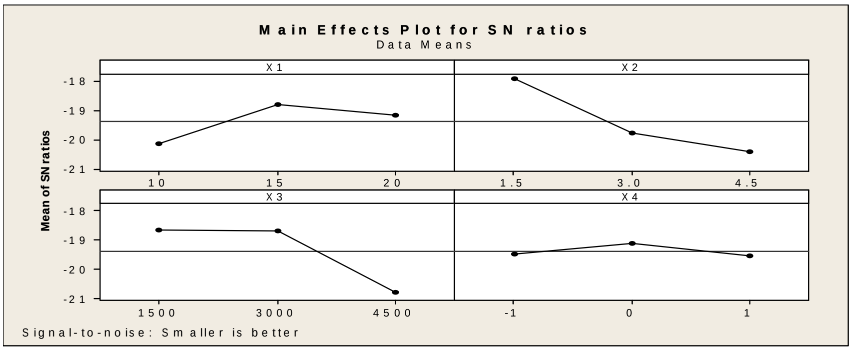

Figure 1: Signal to Noise Plot for Surface Roughness

Similarly the S/N ratio for each level of each factor is obtained and the results of S/N ratio for each level are shown in table 3.4, the best combination of parameters can be identified by selecting the highest difference value from each factor.

Table 5: Response Table of Surface Roughness

Level	Gas Pressure	Cutting Speed	Laser Power	Focal Point Position
1	-20.15	-17.93	-18.67	-19.48
2	-18.81	-19.78	-18.7	-19.11
3	-19.18	-20.43	-20.77	-19.54
Delta	1.34	2.49	2.1	0.43
Rank	3	1	2	4

KERF TAPER

The frequency test (F-test) is utilized in statistics to analyze the significant effects of the parameters, which form the quality characteristics. Table 3.5 shows the result of ANOVA analysis of S/N ratio for surface roughness. This analysis was carried out for a level of significance of 5%, i.e., for 95% a level of confidence.

Table 6: ANOVA Table for KT

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Gas Pressure	2	233.69	233.69	116.847	15.16	0
Cutting Speed	2	18.98	18.98	9.492	1.23	0.315
Laser Power	2	300.84	300.84	150.422	19.51	0
Focal Point Position	2	58.99	58.99	29.493	3.83	0.041
Resiual Error	18	138.75	138.75	7.708		
Total	26	751.26	751.26			

The main effects of input parameters are shown in figure2 with the help of Signal to Noise. The Kerf Taper (KT) decreases with increasing in Gas Pressure but after 15 bar it's drastically coming down, but in case of KT, cutting speed is not influencing much more. The KR is drastically increasing with increase in Laser Power. In case of Focal point, there is no much difference.

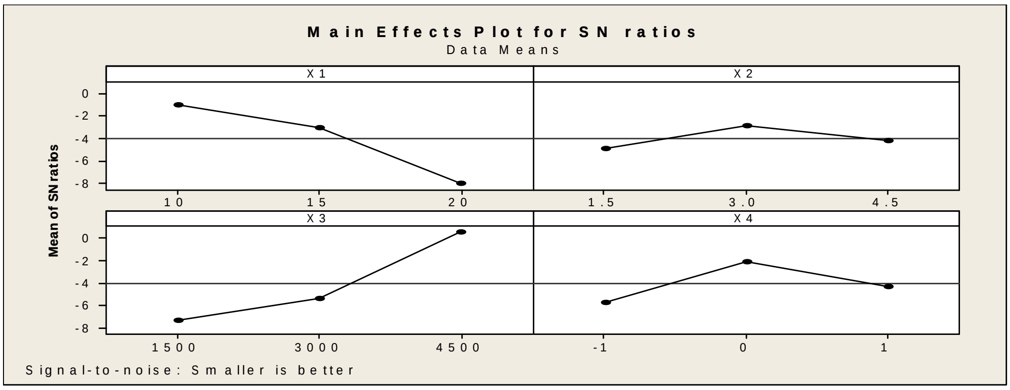

Figure 2: Signal to Noise Plot for Kerf Taper

Based on the ANOVA results in Table 3.5 the percentage contribution of various factors to surface roughness is identifiable. Here, Cutting Speed is the most influencing factor followed by Laser Power. The percentage contribution of speed and Laser Power towards Kerf Taper is 40.04% and 31.10% respectively.

Table 7: Response Table of Surface Roughness

Level	Gas Pressure	Cutting Speed	Laser Power	Focal Point Position
1	-1.0504	-4.949	-7.3062	-5.7054
2	-3.0404	-2.9282	-5.3698	-2.115
3	-8.0436	-4.2572	0.5416	-4.314
Delta	6.9932	2.0208	7.8478	3.5904
Rank	2	4	1	3

D. Response Model

A regression analysis has been used for developing the second order regression models for responses KT and SR. In order to understand the effect of control factors on the responses, first order, second order and interactions between different control factors have been considered.
The final model for the KT and SR obtained are as follows,

$$
\begin{aligned}
SR = {} & 19.0 - 1.37\ X1 + 1.25\ X2 - 0.00271\ X3 - 1.02\ X4 + 0.0331\ X1^2 \\
& - 0.193\ X2^2 + 0.000000\ X3^2 + 0.393\ X4^2 + 0.0535 X1*X2 \\
& + 0.000042\ X1*X3 + 0.0426\ X1*X4 - 0.000016\ X2*X + 0.106 X2*X4 \\
& + 0.000031\ X3*X4
\end{aligned}
$$

$$
\begin{aligned}
KT = {} & 2.77 - 0.196\ X1 - 0.305\ X2 + 0.000141\ X3 + 0.505\ X4 + 0.0126 X1^2 \\
& + 0.0708\ X2^2 - 0.000000\ X3^2 + 0.448\ X4^2 - 0.0117\ X1*X2 \\
& - 0.000004\ X1*X3 - 0.0639\ X1*X4 + 0.000007\ X2*X3 \\
& + 0.0386\ X2*X4 + 0.000037\ X3*X4
\end{aligned}
$$

Where X1 is Gas Pressure, X2 is Cutting Speed, X3 is Laser Power and X4 Focal Point

E. Multi Objective Optimization

For multiple objective problems, the objectives are generally conflicting, preventing simultaneous optimization of each objective. Many, or even most, real engineering problems actually do have multiple objectives, i.e., minimize cost, maximize performance, maximize reliability, etc. These are difficult but realistic problems. GA are a popular meta-heuristic that is particularly well-suited for this class of problems. Traditional GA is customized to accommodate multi objective problems by using specialized fitness functions and introducing methods to promote solution diversity.

For the optimization, the objective function has been defined in C # in M-files. Regression equation has been used as objective function within the parameters ranges shown in Table2. After defining objective function, next step is to select the critical parameters of selection, cross over and mutation such as population size, population type, crossover and mutation probability. In this analysis population size= 200, population type =double vector, crossover probability=0.8, mutation probability=0.07, Maximum Generations=800. After selecting these parameters, the optimization solver has been run and after 800 generations, the optimization has been terminated.

Out of different initial scores and formed different children based on crossover and mutation, 50 optimum solutions have been obtained based on the best fitness values (shown in table 3.7). In multi-objective optimization, there has been found a set of optimal solutions in place on single solution. The o ptimal solution will be that solution by which the objective of the production has been fulfilled in Table number 8.

Table 7: Response Table of Surface Roughness

S NO.	**Gas Pressure**	**Cutting Speed**	**Laser Power**	**Focul Point**	**KT**	**SR**
1	10.2347	1.8233	1962.4189	0.9515	2.166	15.5771
2	10.3597	1.8642	4258.7775	-0.8095	2.2577	10.9954
3	10.4002	1.6873	1982.0437	0.3397	1.841	14.6522
4	10.4655	2.4369	3181.513	0.118	1.8592	16.4644
5	10.5343	1.9152	2252.7547	-0.7432	2.0515	15.9823
6	10.85	2.3496	3397.2205	0.0055	1.8903	15.7554
7	10.8529	2.6813	3883.9852	-0.1895	1.9346	16.6843
8	10.8626	2.944	4442.5315	0.0425	1.9987	16.9145
9	10.8681	2.6688	3954.4726	-0.643	2.0853	16.679
10	11.0509	2.3232	4102.9895	0.3759	2.0583	14.1224
11	11.2499	1.8804	2329.3476	0.6965	2.0222	15.4838
12	11.5761	1.8342	4097.4312	-0.8571	2.4002	11.8118
13	11.6001	1.9895	3221.5739	-0.5752	2.1163	14.622
14	11.6327	1.5822	4000.61	0.6909	2.2902	9.9221
15	11.6397	1.5558	4330.4677	0.4098	2.2044	8.9517
16	11.6777	1.8696	3337.1295	0.106	1.9798	13.3323
17	11.682	2.5173	4409.6786	0.5113	2.1568	15.2469
18	11.6955	2.0845	2749.2745	-0.6094	2.09	16.4003
19	11.7108	1.762	2637.0885	-0.2153	1.962	14.2873
20	12.0118	2.1241	3934.7628	0.5904	2.1665	13.9844
21	12.0805	2.092	3128.4657	-0.1622	1.9761	15.6164
22	12.321	1.8525	3506.6738	0.3486	2.072	13.1983
23	12.8249	1.6594	3934.3092	-0.2079	2.2083	11.2091
24	12.8419	2.0124	3539.0343	-0.4991	2.2335	14.8019
25	12.9391	1.523	3238.6148	0.2014	2.1255	11.6923
26	13.0997	2.2199	4270.5544	-0.7241	2.4399	15.0137
27	13.2329	2.2679	3772.2801	0.5465	2.168	16.3651
28	13.8033	2.2042	4376.1096	-0.2847	2.2972	15.0642
29	13.9462	1.626	3997.7321	-0.0113	2.3014	11.3911

30	14.0992	1.5203	2441.2152	-0.0945	2.2203	13.9775
31	14.1908	1.9332	3258.0445	0.2241	2.1747	15.6036
32	14.1908	1.9332	3112.1778	0.2241	2.1592	15.9154
33	14.1908	1.9332	3112.1778	0.2241	2.1592	15.9154
34	14.1908	1.9332	3112.1778	0.2241	2.1592	15.9154
35	14.1908	1.9332	3112.1778	0.2241	2.1592	15.9154
36	14.1908	1.9332	3112.1778	0.2241	2.1592	15.9154
37	14.1908	1.9332	3112.1778	0.2241	2.1592	15.9154
38	14.1908	1.9332	3112.1778	0.2241	2.1592	15.9154
39	14.1908	1.9332	3112.1778	0.2241	2.1592	15.9154
40	14.1908	1.9332	3112.1778	0.2241	2.1592	15.9154
41	14.1908	1.9332	3112.1778	0.2241	2.1592	15.9154
42	14.4714	1.578	3711.6941	0.6758	2.4046	12.0165
43	15.4378	1.8352	2921.1035	0.01	2.3604	16.4318
44	15.7956	1.6199	3007.9501	-0.2438	2.5855	14.6353
45	16.0106	1.5404	3282.8494	0.0069	2.5572	13.4419
46	16.6992	1.6655	4094.9171	0.1462	2.6842	13.4522
47	17.1834	1.7017	4210.7338	0.1141	2.7842	13.9648
48	17.3288	1.5817	4406.055	-0.4875	3.1867	12.594
49	17.3303	1.585	2704.2182	0.2682	2.6683	15.9822
50	17.9457	1.5086	4280.0448	-0.0468	3.057	12.5275

III. CONCLUSIONS

The difficult-to-cut Titanium alloy sheet has been successfully cut using a pulsed CO2 laser beam. The hybrid approach of design of experiment (DOE) and genetic algorithm (GA) has simultaneously optimized the responses kerf taper and surface roughness. The main findings of the experiment are given below,

- The Cutting speed has been found the most significant control factor followed by Laser Power for Surface roughness where as Laser Power and Assist gas pressure have been found the significant factors for kerf taper.
- The suggested optimal solutions may be used for cutting of Titanium alloy sheet grade 5 (Ti-6Al-4V).

REFERENCES

[1] Biffi CA, Lecis N, Previtali B, Vedani M, Vimercati GM. *Fiber laser microdrilling of Titanium and its effect on material microstructure*. International Journal of Advanced Manufacturing Technology 2011;54:149–60.
[2] Dornfeld DA, Kim JS, Dechow H, Hewson J, Chen LJ. *Drilling burr formation in Titanium alloy Annals of CIRP* 1999;48:73–6.
[3] Steen WM. *Laser Material Processing.3rd edn*. New York: Springer; 1991.
[4] Dubey A., Yadava V., Laser beam machining—*A review, Int. Journal of Machine Tools & Manufacture 48* (2008) 609–628
[5] Ilzabel L, Álvarez MJ, Viles E, Tanco M (2008). P*ractical applications of design of experiments in the field of engineering: A bibliographicIal review*. Qual. Reliab. Eng. Int., 24(4): 417-428
[6] Huehnlein K., Tschirpke K., Helimann R., *Optimization of laser cutting processes using design of experiments*, Physics Procedia 5 (2010) 243–252
[7] Chen M., Ho Y., Hsiao W., Wu T., Tseng S., Huang K., *Optimized laser cutting on light guide plates using grey relational analysis, Optics and Lasers in Engineering*, 49 (2011) 222–228
[8] Dubey AK, Yadava V. *Optimization of kerf quality characteristics during pulsed laser cutting of aluminium alloy sheet. Journal of Materials Processing* Technology 2008;204:412–8.
[9] Sharma A, Yadava V, Rao R. *Optimization of kerf quality characteristics during ND:YAG laser cutting of nickel based superalloy sheet for straight and curved cut profiles*. Optics and Lasers in Engineering 2010;48:915–25.
[10] Caydas U, Hascalik A. *Use of grey relational analysis to determine optimum laser cutting parameters with multi-performance characteristics.* Optics and Laser Technology 2008;40:987–94.
[11] Shanjin L, Yang W. *An investigation of pulsed laser cutting of Titanium alloy sheet. Optics and Lasers in Engineering* 2006;44:1067–77.
[12] RaoBT, KaulR,TiwariP, NathAK. *Inert gas cutting of Titanium sheet with pulsed modeCO2 laser*. Optics and Lasers in Engineering2005;43:1330–48.

[13] AlmeidaIA, RossiWD, LimaMSF, BerrettaJR ,NgueiraGEC, WetterNU, Vieira Jr. ND .*Optimization of Titanium cutting by factorial analysis of pulsed Nd:YAG laser parameters*. Journal of Materials Processing Technology 2006;179:105–10.

[14] Nakhjavani OB, Ghoreishi M. *Multi criteria optimization of laser percussion drilling process using artificial neural network model combined with genetic algorithm*. Materials and Manufacturing Processes 2006;21:11–8.

[15] PradhanMK, BiswasCK. *Neuro-fuzzy model and regression model a comparison study of MR Rinelectrica ldischarge machining of D2 tool steel*, international journal of mathematical. Physical and Engineering Sciences 2009;3(1):48–53.

[16] C aydas U,Hasc-alık A,EkiciS. *An adaptive neuro-fuzzy inference system (ANFIS) model for wire-EDM*.Expert Systems with Applications2009;36: 6135–9.

[17] PatowariPK, SahaP, MishraPK. *Artificial neural network model insurface modification by edm usingTungsten–Copper powder metallurgy sintered electrodes*. International Journal of Advanced Manufacturing Technology 2010;51:627–38.

[18] MajiK, PratiharDK. *Forward and reverse mapping of electrical discharge machining process using adaptive network based fuzzy inference system*. Expert Systems with Applications 2010;37:8566–74.

[19] Sivarao P, Brevern NSM, Tayeb VC. *Vengkatesh, modeling, testing and experimental validation of laser machining micro quality response by artificial neural network*. International Journal of Engineering & Technology 2009;09:161–6.

[20] Syn CZ, Mokhtar M, Feng CJ, Yupiter HP. *Manurung, approach to prediction of laser cutting quality by employing fuzzy expert system*. Expert Systems with Applications 2011;38:7558–68.

[21] Jimin C, Jianhua Y, Shuai Z, Tiechuan Z, Dixin G. *Parametric optimization of non vertical laser cutting*. International Journal of Advanced Manufacturing Technology 2006;33:469–73.

[22] Ross PJ. *Taguchi Techniques for Quality Engineering.2nd edn*. New Delhi (India): Tata Mcgraw-Hill Publishing Company Ltd; 1996.

