Optimization using GRA for MS Grade through Fiber Laser Cutting Process

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Abstract - Laser beam machining (LBM) is one of the most widely used thermal energy based non-contact type advance machining process which can be applied for almost whole range of materials. This work studied the performance of fiber laser cutting of mild steel. The experiment was focused on the cut quality with surface roughness and kerf width with two assistant gases pressure. After analysis the cutting result, several conclusions were made. Although the best result got in the experiment is not perfect as predicted, the whole result of the test can be accepted. This work an application of the grey relational analysis (GRA) to directly optimize laser cutting of a mild steel sheet using two performance characteristics. From twenty seven experiments based on the orthogonal array of L_{27}, an O_2 pressure of 1 bar, a N_2 pressure of 15 bar, and a laser power of 1100 watt were found to be the best parameters for laser cutting of a mild steel with two assistant gases pressure. Moreover, the analysis of variance (ANOVA) is also employed to determine the contribution of each control parameter on the cut quality characteristics. The three largest measured contributions on the cut quality in decreasing order are the O_2 pressure, the N_2 pressure, and the laser power. The optimal combination from both the GRA and the Taguchi methods from 27 experiments is the same. Finally, confirmation experiments are performed to ensure the robustness of the GRA predicted optimal configuration for laser cutting of mild steel. Compared with single assist gas laser, a higher cutting speed was achieved by fiber laser with two assistant gases pressure.

Keywords – Fiber laser, Taguchi, ANOVA, grey relational grade, Gas pressure, Laser power

I. INTRODUCTION

1.1 Laser

Laser (light amplification by stimulated emission of radiation) is a coherent and amplified beam of electro-magnetic radiation [1].

1.2 Laser Cutting Process

Laser cutting is a common manufacturing process employed to cut many types of materials. Materials which may be cut included ferrous metal, non ferrous metal, stone, plastic, rubber and ceramic. Laser cutting works by directing a high power pulsed laser at a specific location on the material to be cut. The energy beam is absorbed into the surface of the material and the energy of the laser is converted into the heat, which melt or vaporize the material. Additionally gas is focused or blown into the cutting region to expel or blow away the molten melt and vapor from cutting path.

There are several advantage of laser cutting over mechanical cutting, since the cut is performed by the laser beam, there is no physical contact with the material therefore contaminates cannot enter or embed into the material. Laser cutting can produce high quality cut, complex cut, cut several part simultaneously, produce clean cutting edge which require minimal finishing as well as low edge load during cutting which will reduce distortion [2].

1.3 Fiber Laser Cutting

For a Fiber Laser the gain medium is an Ytterbium doped glass fiber, with the excitation energy being provided by laser diodes, operating around 950nm, coupled by various schemes into the core of the doped fiber. The laser beam wavelength is typically in range 1.07µm to 1.09µm. obviously the physical dimensions of the gain medium for the Fiber Laser are very different from other laser types. A Nd:YAG rod might be 200mm, a CO_2 discharge around 2m, but the gain fiber in a Fiber Laser will be 10's of meters long.

The reflectors used in the Fiber Laser are physically very different from traditional lasers. Typically the mirror will be formed from a dielectric coating on substrate; which will be transmissive at the laser wavelength for the output coupler. For the Fiber Laser, Bragg Gratings written into the core of a fiber are used. These Fiber Bragg Gratings (FBGs) consist of periodic refractive index variations. The longitudinal period of the grating determines the wavelength of the reflected light, and the magnitude of the variation controls the reflected percentage [3].

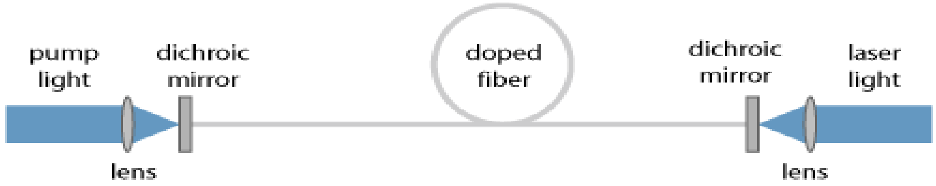

Figure 1. Scheme of a simple fiber laser

1.3.1 Advantages of fiber laser

The advantages of the Fiber Laser for Industrial applications can be summarized as follows:

- Good reliability and lifetime,
- High stability of laser output leading to consistency of processing,
- Small size of overall unit,
- Generally longer warranty than standard lasers,
- Option of air cooled or water cooled up to a few hundred watts output power,
- Lower price than equivalent power traditional laser,
- Integrated damage protection against back reflection issues,
- Control software offering full functionality and ability to be integrated into system level controllers,
- Fault diagnostics for improved warning or alarm identification,
- End of life warning for tracking diode lifetimes,
- Reliable, stable and linear power monitor integrated to laser,
- Single sourcing for laser and process tools (cutting head, welding head or galvanometer based scanners),
- Ability to increase processing performance of reflective materials through periodic enhancements to laser peak power [3].

II. LITERATURE SURVEY

K. Abdel Ghany, M Newishy, In this article they evaluated the optimum laser cutting parameters for 1.2 mm austenitic stainless steel sheets by using pulsed and CW Nd:YAG laser beam and nitrogen or oxygen as assistant gases, each one separately. For cutting stainless steel by pulsed and CW Nd:YAG laser, it was shown that the laser cutting quality depends mainly on the laser power, pulse frequency, cutting speed and focus position. Comparing with oxygen, nitrogen produced brighter and smoother cut surface with smaller kerf, although it did not prove to be economical. In CW mode, the speed can be increased to more than 8 m/min with equivalent power and gas pressure [4].

Shang – Liang Chen, They investigated the effects of gas composition on high power CO_2 laser cutting of mild steel. The gas mixtures used were composed of oxygen, argon, nitrogen, helium. It was found that a high purity of oxygen is required for the high-performance CO_2 laser cutting of mild steel. Only a tiny oxygen impurity (1.25%) will reduce the maximum cutting speed by 50% [5].

A. Riveiro et. al., They were studied that the process relies on the removal of the melted material with the aid of a pressurized assist gas. Among the main variables controlling the process, the assist gas type is an essential factor. This gas is normally chosen taking into account the material to be processed and the required cut quality. While the effect of the utilization of different assists gas is perfectly studied in cutting steels. This work presents a study on the influence of different assist gases (argon, nitrogen, oxygen and air) on the edge quality and its surface chemistry during laser cutting of a typical Al-Cu alloy. After investigation the Results indicate a clear influence of the assist gas nature on the finishing characteristics. Then, from the point of view of quality and efficiency argon is the best choice for processing Al-Cu alloys [6].

B.D. Prajapati et. al., Investigated the effect of laser machine processing parameters such as laser power, gas pressure, cutting speed and thickness effect on measured response such as surface roughness. The experiment was designed according to Taguchi L_{27} orthogonal array with three different level of each input parameter. For result interpretation, analysis of variance (ANOVA) was conducted and optimum parameter is selected on the basis of the signal to noise ratio, which confirms the experimental result. The result indicated that cutting speed and work piece thickness play important role in surface roughness. Cutting speed and thickness of plate have high contribution on surface roughness for both materials [7].

Catherine et. al., Investigated the effects of laser power, cutting speed, focal point position, and assist gas pressure on the cutting performance and cut quality were investigated. The effects of focal point position and assist gas pressure on the striation pattern (cut surface roughness) were also examined. Low surface roughness was achieved with the focal point position inside the workpiece showing the need for a wider kerf for better melt ejection in thick-section metal cutting. There was also a reduction in surface roughness with increase in assist gas pressure [8].

Zhenhua Xiao et. al., They studied a preliminary test was made in order to investigate effect of the cutting parameters on cut quality. Then the formal fiber laser cutting experiment was made by using 3 mm thickness S355 steel with oxygen as assistant gas. The experiment was focused on the cut quality with maximum cutting speed and minimum oxygen gas pressure. And the cut quality is mainly decided by the kerf width, perpendicularity tolerance, surface roughness and striation patterns. Compared with CO_2 laser, a higher cutting speed was achieved by fiber laser with very low oxygen gas pressure [9].

Ulas Cydas et. al., This paper presents an effective approach for the optimization of laser cutting process of St-37 steel with multiple performance characteristics based on the grey relational analysis. Sixteen experimental runs based on the Taguchi method of orthogonal arrays were performed to determine the best factor level condition. The response table and response graph for each level of the machining parameters were obtained from the grey relational grade. The laser cutting parameters such as laser power and cutting speed are optimized with consideration of multiple-performance characteristics, such as workpiece surface roughness, top kerf width and width of heat affected zone (HAZ). By analyzing the grey relational grade, it is observed that the laser power has more effect on responses rather than cutting speed. It is clearly shown that the above performance characteristics in laser cutting process can be improved effectively through this approach [10].

From the review of literature, it is observed that the Most of the research work on fiber laser was performed by using single assistant gas such as (oxygen or nitrogen) alone and less work has been done by using two assistant gases such as (oxygen and nitrogen) for cutting purpose. So in this work it is proposed to study the effect of different input parameters, namely, oxygen gas pressure, nitrogen gas pressure, and laser power on the surface roughness and kerf width. It is observed that the grey relational analysis has found wide application areas for determining the optimal parameters through different machining process. The purpose of the present work is to carried out the experiment work with two assist gases pressure and to be introduce the use of grey relational analysis in selecting optimal laser cutting conditions on multi performance characteristics, namely, workpiece surface roughness and kerf width. The setting of laser cutting parameters was accomplished using the taguchi experimental design method. Moreover, the most effective factors and the order of importance of the controllable factors to the multi performance characteristics in the laser cutting process were determined by using taguchi, ANOVA and grey relational grade.

III. EXPERIMENTAL PROCEDURE

The experiments were conducted on a Future-X fiber laser cutting machine at sahajanand laser technology limited, Gandhinagar. This machine used a $\gamma = 1$ μm wavelength fiber laser with a nominal power output of 1500 W. The laser beam was focused using a 125 mm focal length lens. The nozzle workpiece stand-off distance was controlled at 1 mm. A 1.6 mm IS-2062 mild steel was used as workpiece material. The chemical composition of the mild steel is provided in Table 1.

Table 1. Nominal chemical composition of mild steel

C	Si	Mn	P	S	Cr	Ni
0.063	0.006	0.223	0.023	0.012	0.022	0.014

Because of the large number of independent parameters that control the laser cutting process. The summary of experimental conditions is listed in Table 2.

Table 2. Laser cutting factors and their levels

Symbol	Cutting factor	Level 1	Level 2	Level 3
A	O2 gas pressure	1	3	5
B	N2 gas pressure	9	12	15
C	Laser power	1100	1300	1500

The experimental results after laser cutting were evaluated in terms of the following measured machining performances: (1) surface roughness (R_a); (2) kerf width (KW). Each test piece was measured 5 times and average value taken for a more accurate reading. The surface roughness of laser cut surfaces was measured from the centerline of the cut edge using a Mitutoyo SJ-201 instrument. The kerf width was measured by using a Nikon profile projector.

In order to achieve best cutting quality, Taguchi's experimental design, an efficient plan, was used for conducting experiments. For this purpose, a L_{27} orthogonal array was used for experiment work (Table 3). The experimental results are summarized in Table 3.

Table 3. Experimental layout using an L_{27} orthogonal array and multi performance results

Exp. No.	INPUT PARAMETERS			OUTPUT PARAMETERS	
	Oxygen Pressure (bar)	Nitrogen Pressure (bar)	Laser Power (watt)	Surface Roughness Ra (μm)	Kerf Width (mm)
1	1	9	1100	1.292	0.314
2			1300	1.965	0.319
3			1500	2.566	0.322
4		12	1100	1.151	0.258
5			1300	1.742	0.261
6			1500	2.464	0.263
7		15	1100	1.131	0.201
8			1300	1.713	0.204
9			1500	2.335	0.209
10	3	9	1100	9.954	0.486
11			1300	11.152	0.482
12			1500	11.457	0.477

13		12	1100	9.547	0.438
14			1300	10.971	0.441
15			1500	11.008	0.444
16		15	1100	9.251	0.384
17			1300	10.408	0.389
18			1500	10.901	0.393
19	5	9	1100	10.411	0.689
20			1300	11.745	0.694
21			1500	11.956	0.698
22		12	1100	10.258	0.596
23			1300	11.667	0.599
24			1500	11.848	0.604
25		15	1100	10.156	0.554
26			1300	11.575	0.559
27			1500	11.655	0.565

IV. ANALYSIS OF RESULTS

4.1 Introduction

In design of experiment the results are analyzed due to one or more of the following three objectives.

- To establish the best or the optimum condition for a product or a process.
- To estimate the contribution of individual factors.
- To estimate the response under the optimum conditions.

The optimum condition is identified by studying the main effects of each of the factors. The main effects indicate the general trends of the influence of the factors. Knowing the characteristics, i.e., whether a higher or lower value produces the preferred results, the level of the factors which are expected to produce the best results can be predicted. The knowledge of the contribution of individual factors is a key to deciding the nature of the control to be established on a production process [11].

4.2 Analysis of variance (ANOVA)

The analysis of variance (ANOVA) is the statistical treatment most commonly applied to the results of the experiment to determine the percent contribution of each factors. Study of ANOVA table for a given analysis helps to determine which of the significant factors, out of all setting parameters which has to be control and which do not. Once the optimum condition is determined, it is usually good practice to run a confirmation experiment. The analysis of the partial experiment must include an analysis of confidence that can be placed in the results. So analysis of variance is used to provide a measure of confidence. Analysis provides the variance of controllable and noise factors. By understanding the source and magnitude of variance, robust operating conditions can be predicted [11].

4.2.1 Analysis of variance of surface roughness for Mild Steel

Table 4. Analysis of variance for surface roughness of Mild Steel

Sources of variation	DOF	Sum of squares S	Variance (mean Square)	Variance ratio F	Percentage contribution P
Factor A	2	495.6749	247.8375	6279.186	97.70183
Factor B	2	0.633854	0.316927	8.02963	0.124938
Factor C	2	10.23616	5.118081	129.6712	2.017637
Error E	20	0.789394	0.03947	1	0.1556
Total	26	507.3343			100

Above analysis shows the percentage contribution of individual parameters on surface roughness. The percentage contribution of oxygen pressure is 97.61%, nitrogen pressure is 0.062%, and laser power is 1.83%. Parametric analysis is carried out for the quality of the sample. i.e. surface roughness. This parametric analysis (ANOVA) shows the percentage contribution of parameters individually as sown in Table 4.

4.2.2 Analysis of variance of kerf width for Mild Steel

Table 5. Analysis of variance for kerf width of Mild Steel

Sources of variation	DOF	Sum of squares S	Variance (mean Square)	Variance ratio F	Percentage contribution P
Factor A	2	0.571412	0.285706	2184.048	90.3197
Factor B	2	0.058458	0.029229	223.4391	9.2402
Factor C	2	0.000168	0.000084	0.642412	0.02657
Error E	20	0.002616	0.000131	1	0.4135
Total	26	0.632654			100

Above analysis shows the percentage contribution of individual parameters on kerf width. The percentage contribution of oxygen pressure is 90.32%, nitrogen pressure is 9.24%, and laser power is 0.0266%. Parametric analysis is carried out for the quality of the sample. i.e. kerf width. This parametric analysis (ANOVA) shows the percentage contribution of parameters individually as sown in Table 5.

4.2.3 Main effect plot for S/N ratios of surface roughness and kerf width

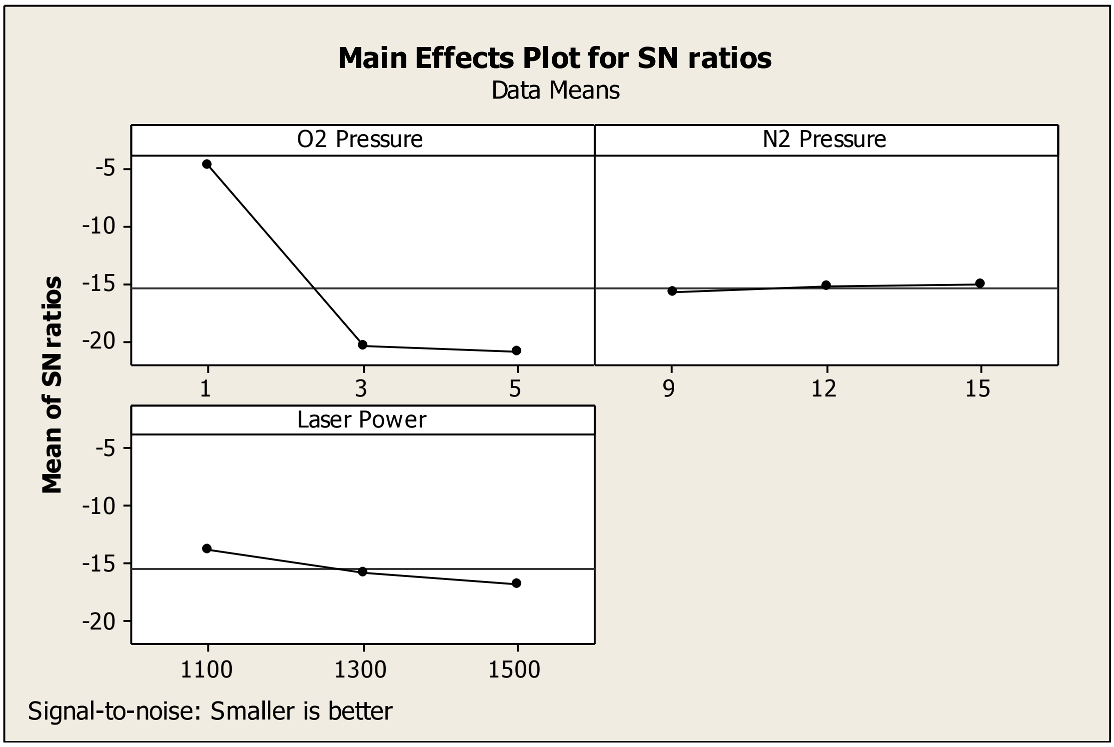

Figure 2. Main effect plot for S/N ratios of surface roughness

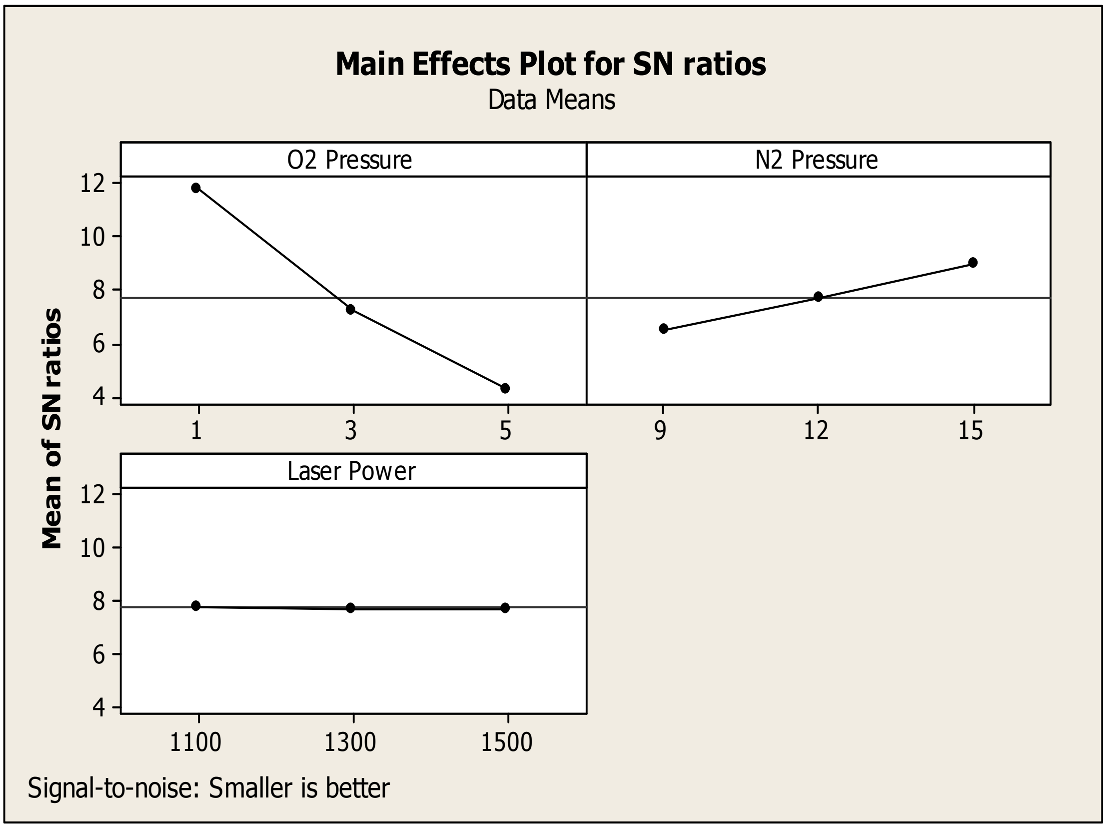

Figure 3. Main effect plot for S/N ratios of kerf width

Main effects plot for the SN ratios are shown in Figure 2 & 3 which shows the variation of surface roughness and kerf width with respect to input parameters.

Above graphs shows the effect of output parameters with respect to input parameters. This graph divide in three part (O_2 pressure, N_2 pressure and laser power) that shows the individual effect on surface roughness and kerf width value. In every graph that has higher S/N ratio value that parameters are better as compare to other.

V. GREY RELATIONAL ANALYSIS

In grey relational analysis, this analysis can be used to represent the grade of correlation between two sequences so that the distance of two factors can be measured discretely. In the case when experiments are ambiguous or when the experimental method cannot be carried out exactly, grey analysis helps to compensate for the shortcoming in statistical regression. Grey relation analysis is an effective means of analyzing the relationship between sequences with less data and can analyze many factors that can overcome the disadvantages of statistical method [10].

5.1 Data pre-processing

Data pre-processing is a process of transferring the original sequence to a comparable sequence. For this purpose, the experimental results are normalized in the range between zero and one.

If the target value of original sequence is infinite, then it has a characteristic of ‘‘the-larger-the-better’’. The original sequence can be normalized as follows:

$$x_i(k) = \frac{y_i(k) - \min y_i(k)}{\max y_i(k) - \min y_i(k)} \qquad \ldots\ldots (1)$$

If the expectancy is "the smaller the better" than the original sequence should be normalized as follows:

$$X_i(k) = \frac{\max y_i(k) - y_i(k)}{\max y_i(k) - \min y_i(k)} \quad \text{.......... (2)}$$

Here X_i (k) is the value after grey relational generation, min y_i (k) is the smallest value of y_i (k) for the k_{th} response, and max y_i (k) is the largest value of y_i (k) for the k_{th} response and y_i (k) is the desired value [10].

5.2 Grey relational coefficient and grey relational grade

Following data pre-processing, a grey relational coefficient is calculated to express the relationship between the ideal and actual normalized experimental results. The Grey relation coefficient can be express as follows.

$$\zeta_i(k) = \frac{\Delta_{min} + \zeta.\Delta_{max}}{\Delta_{0i}(k) + \zeta.\Delta_{max}} \quad \text{.......... (3)}$$

Where Δ_{0i} (k) is the deviation sequence of the reference sequence x_0 (k) and the comparability sequence xi (k), namely,

$$\Delta_{0i} = \left| x_0(k) - x_i(k) \right| \quad \text{.......... (4)}$$

ζ is distinguishing or identification coefficient: $\zeta \in [0,1]$, $\zeta = 0.5$ is generally used.

After obtaining the Grey relation coefficient, its average is calculated to obtain the Grey relation grade. The Grey relation grade is defined as follows:

$$\gamma_i = \frac{1}{n} \sum_{k=1}^{n} \zeta_i(k) \quad \text{.......... (7)}$$

Where n = number of process responses [10].

From equation 2, 4 and 7 this grey relational analysis carried out.

Table 6. Grey relational analysis

Experiment No.	Normalize value of SR	Normalize value of KW	GRC of SR	GRC of KW	GRG	Grade No.
1	0.9851	0.7726	0.9711	0.6874	0.8293	6
2	0.9230	0.7626	0.8665	0.6780	0.7723	8
3	0.8674	0.7565	0.7904	0.6725	0.7315	9
4	0.9982	0.8853	0.9963	0.8134	0.9049	3
5	0.9436	0.8793	0.8986	0.8055	0.8520	5
6	0.8769	0.8753	0.8024	0.8003	0.8014	7
7	1.0000	1.0000	1.0000	1.0000	1.0000	1
8	0.9462	0.9940	0.9029	0.9881	0.9455	2
9	0.8888	0.9839	0.8180	0.9688	0.8934	4
10	0.1849	0.4266	0.3802	0.4658	0.4230	16
11	0.0743	0.4346	0.3507	0.4693	0.4100	17
12	0.0461	0.4447	0.3439	0.4738	0.4088	18
13	0.2225	0.5231	0.3914	0.5118	0.4516	13
14	0.0910	0.5171	0.3549	0.5087	0.4318	14

15	0.0876	0.5111	0.3540	0.5056	0.4298	15
16	0.2499	0.6318	0.4000	0.5759	0.4879	10
17	0.1430	0.6217	0.3685	0.5693	0.4689	11
18	0.0975	0.6137	0.3565	0.5641	0.4603	12
19	0.1427	0.0181	0.3684	0.3374	0.3529	25
20	0.0195	0.0080	0.3377	0.3351	0.3364	26
21	0.0000	0.0000	0.3333	0.3333	0.3333	27
22	0.1569	0.2052	0.3723	0.3862	0.3792	20
23	0.0267	0.1992	0.3394	0.3844	0.3619	23
24	0.0100	0.1891	0.3356	0.3814	0.3585	24
25	0.1663	0.2897	0.3749	0.4131	0.3940	19
26	0.0352	0.2797	0.3413	0.4097	0.3755	21
27	0.0278	0.2676	0.3396	0.4057	0.3727	22

VI. RESULTS AND DISCUSSIONS

6.1 Effect of O_2 pressure, N_2 pressure and laser power on surface roughness

In the investigation on the effect of O_2 pressure during fiber laser cutting of mild steel it found from the analysis plot that when the O_2 pressure increases the Surface roughness of mild steel material increases, an increase in N_2 pressure rate leads to a little decrease in the Surface roughness, and Increase in laser power increases surface roughness little as shown in Figure 2.

6.2 Effect of O_2 pressure, N_2 pressure and laser power on kerf width

In the investigation on the effect of O_2 pressure during fiber laser cutting of mild steel it found from the analysis plot that when the O_2 pressure increases the kerf width of mild steel material increases, an increase in N_2 pressure rate leads to a decrease in the kerf width, and Increase in laser power it affects very little to kerf width as shown in Figure 3

6.3 Effect of O_2 pressure, N_2 pressure and laser power on cutting speed

In the investigation on the effect of combine O_2 pressure and N_2 pressure during fiber laser cutting of mild steel it found from the pilot experiment that the cutting speed increases to 9200 mm/min which is very high speed as compare to single assist gas but at very high speed the surface roughness is not good so consider the optimum cutting speed 4000 mm/min for good surface roughness in this work.

6.4 Optimum level from the effect plot for surface roughness and kerf width

From the main effect plot of S/N ratios for surface roughness and kerf width can get easily the optimum condition from the plot. For surface roughness and kerf width the optimum level of oxygen gas pressure is 1 bar, nitrogen gas pressure is 15 bar, and laser power is 1100 watt. So from the level condition is found that it is the exp. No. 7 is optimum condition for the process.

6.5 Optimum level from grey relational analysis

According to performed experimental design, it is clearly observed from Table 19 and the grey relational grade graph which shows the change in the response when the factors go from one level to other that the fiber laser cutting parameters setting of experiment no. 7 has the highest grey relational grade. Thus, the seventh experiment gives the best multi-performance characteristics among the 27 experiments.

VII. CNCLUSIONS

- The fiber laser machining of mild steel was experimentally investigated. Taguchi's method was used for conducting and analyzing the experiments. The machining parameters selected for the process were oxygen gas pressure, nitrogen gas pressure and laser power. Researchers have already attempted several systematic procedures for optimizing the multiple responses of fiber laser cutting process. There also exist some other approaches which may be quite effective for multiple response optimizations of fiber laser cutting processes.

- Fiber laser is an adequate process to cut sheet metal with good surface finish with less time.
- The best result got in the experiment is not perfect as predicted, such as there is still higher surface roughness with single assistant gas in laser cutting, which means more material was remove in the fiber laser cutting process. However, the whole result of the test can be accepted, such as a relatively higher cutting speed compared with single assistant gas laser cutting. Therefore, the experiment basically achieved the purpose of this study which is to reveal the cutting performance and how cutting parameters affect fiber laser cutting mild steel.
- Oxygen gas pressure is found the most significant effect on surface roughness and kerf width. Increase in oxygen gas pressure, value of surface roughness and kerf width is increases. That it is because the oxygen participates in an exothermic reaction with the mild steel. When a high pressure is used, it always causes over burning effect.
- Laser power is found to have effect on surface roughness and kerf width. Increase in laser power, value of surface roughness and kerf width is increases. The reason can be clear that high power intensity enhances the material removal rate from the workpiece. Therefore, the value of kerf width and surface roughness increased at high laser output power levels.
- Nitrogen gas pressure is found to have effect on surface roughness and kerf width. Increase in nitrogen gas pressure, value of surface roughness is little decrease and value of kerf width is decrease effectively with nitrogen gas pressure. The efficiency of melt removal from the cut kerf plays a very important role on the cutting performance and the resulting cut edge quality. The rate of melt removal from the cut kerf mainly depends on high nitrogen gas pressure.
- In this work, a GRA based on the Taguchi method is used to directly integrate two laser cutting quality characteristics of a mild steel sheet into a grey relational grade. The grade obtained for each experiment can immediately reflect the actual cutting results, including the surface roughness and kerf width. An optimal combination of cutting parameters and the effect of each cutting parameter is obtained. The optimal combination from both the GRA and the Taguchi methods from 27 experiments is the same. However, compared to the results using the Taguchi method with a designed score transformation, the GRA approach is significantly simpler due to the weighting factors for different quality requirements.

REFERENCES

1. “Non Conventional Machining” by P.K. Mishra, Narosa Publication House, Third Edition 2005, pp.147-159.
2. Introduction to Laser Material Processing by Columbia University.
3. “Introduction to Fiber Lasers and their Applications”, By Dr Mark Richmond (Product Manager – JK Fiber Lasers) & Dr Mo Naeem (Worldwide Applications Expert, GSI Group, Laser Division, Cosford Lane, Rugby, Warwickshire, CV21 1QN, UK).
4. K.A. Ghany, M.Newishy, “Cutting of 12mm thick austenitic stainless steel sheet using pulsed and CW Nd:YAG laser”(JMPT 2005), pp. 438-447.
5. Shang – Liang Chen, “The effect of gas composition on the CO_2 laser cutting of mild steel” (Journal of Materials Processing Technology 73 (1998) 147-159).
6. A.Riveiro et al. “The Role of the Assist Gas Nature in Laser Cutting of Aluminium Alloys” (Physics Procedia 12 (2011)), pp. 548-554.
7. B.D.Prajapati, R.J.Patel, B.C.Khatri, “Parametric Investigation of CO2 Laser Cutting of Mild Steel and Hardox-400 Material” (IJETAE, Volume 3, Issue 4, April 2013), pp. 204-208.
8. Wandera, C., Salminen, A. and Kujanpää, “Inert gas cutting of thick-section stainless steel and medium section Aluminium using a high power fiber laser” (Journal of Laser Applications, 21 (3), 154 - 161).
9. Zhenhua Xiao, “Fiber laser cutting of mild steel” at Lappeenranta University of Technology, Lappeenranta, Finland on the 12th of February 2007.
10. Ulas Cydas, “Use of the grey relational analysis to determine optimum laser cutting parameters with multi-performance characteristics” (Optics & Laser Technology 40 (2008) 987–994).
11. R.K Roy “A primer on the taguchi method”, Van Nostrand Reinhold, Neyyork, USA.

