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Multi-Objective Optimization of Laser Cutting Process Parameters for Mild Steel

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ABSTRACT

Laser cutting is a popular process, which finds wide application in various manufacturing industries because of its precision of operation and low cost. Laser cutting, being a non-contact process, does not involve any mechanical cutting forces and tool wear. To maintain a high production rate and an acceptable level of quality for the cut parts, there is need to select the optimum combination of process parameters. This paper presents method of optimization for multi performance characteristics of LBC process for mild steel. Surface roughness (SR) and material removal rate (MRR) are multi performance characteristics and nozzle dia., gas pressure, cutting speed and cutting power are taken as input process parameters. Grey relational analysis (GRA) technique is used for optimization. ANOVA technique is also used to find significant and sub significant parameter. This experimental work will be helpful in deciding optimum parameters and to improve LBC process.

Keywords: ANOVA, Grey Relational Analysis LBC, Mild Steel, Taguchi Method

I. INTRODUCTION

Laser beam cutting process uses focused laser light, by which work piece material is locally melted. The melt is then coming out of the kerf with an assist gas that flows coaxial with the laser beam. When using oxygen as assist gas, it will drag the melt away as well as provide exothermic reaction in the cutting section enhancing the energy available for increasing the cutting speed. CO_2 laser cutting is one of the processes which is used to cut sheets and having ability to produce accurate cut edges and surfaces with higher accuracy and surface finish. Post processing is not required for laser cut parts.

Ulas Caydas et al. (2008) presented an effective approach for the optimization of laser cutting process of st-37 steel based on the grey relational analysis and Taguchi method of orthogonal arrays. B.Adelmann et al. (2011) reported on a fast laser cutting optimization algorithm (FALCOA) to optimize the laser parameters for the laser fusion cutting of 1 mm aluminium sheets. Avanish Kumar Dubey et al. (2012) experimented on the laser cutting

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of Duralumin sheet and Fuzzy logic theory has been applied to compute the fuzzy multi-response performance index. The confirmation tests show considerable reduction of 50% to 71% in kerf deviations at top and bottom sides. Koji Hirano et al. (2011) observed striation generation mechanism in inert gas laser cutting of 3mm thick low carbon mild steel. Vinod Yadava et al. (2013) optimized cut quality characteristics during Nd:YAG laser cutting of aluminium alloy thin sheet with the use of Taguchi Methodology (TM) and Response Surface Methodology (RSM) in combination. Optimum kerf deviation and kerf taper are obtained by applying grey relational analysis (GRA) with entropy measurement (EM). In the fusion cutting of stainless steel, the minimum roughness is reached at the maximum cutting speed. The maximum cutting speed has the higher value in the fibre-laser case at the same laser power (V.B.Shulyatyev et al. 2014).

II.EXPERIMENTAL PROCEDURE

The CO_2 laser cut quality of mild steel sheet of grade XT07 is monitored experimentally. The quality characteristics under consideration are surface roughness and material removal rate (MRR). They are monitored with the variation in input parameters which are nozzle dia. (mm), gas pressure (MPa), cutting power (watt) and cutting speed (mm/min). Assist gas used is oxygen. The process parameters optimized by grey relational analysis technique and analyzed by ANOVA technique.

2.1 Work piece Material

The workpiece material used to carrying out experiment was mild steel sheet of XT07 grade. The dimensions of the workpiece were “100 x 50 x 4 mm”. Elongated hole of “30×20mm” size was cut on the work piece as. Chemical composition of material is given in Table 1.Mild steel of grade XT07 used for generator canopy parts.

Table 1 : Chemical composition of mild steel

Element	SI	S	P	C	Mn
Wt %	0.076	0.01	0.018	0.065	0.51

2.2 Experimental setup

Experiments were conducted on AMADA FO3015 laser centre as shown in Figure 1.it is CO_2 type laser centre. Power output of the machine was 2000 watt for continuous wave and co-ordinates of machine was X-3420 mm, Y-1550mm, Z-200mm. It can cut sheets of mild steel up to 12 mm very effectively. To measure the surface roughness Taylor-Hobson surface profile meter was used. Surface roughness was measured at all four cut faces of sheet and average of all these four values is taken as resulting surface roughness for that laser cut work piece. Measurement of material removal rate was done by using following formula:

$$MRR = \frac{\text{Weight After (gm)} - \text{Weight Before (gm)}}{\text{Cutting Time (min)} + \text{Piercing Time (min)}} \quad (1)$$

$$\text{Cutting Time} = \frac{\text{Perimeter (mm)}}{\text{Cutting Speed (mm/min)}} \quad (2)$$

Perimeter=87.33 mm

Figure 1 Laser Beam Cutting Machine

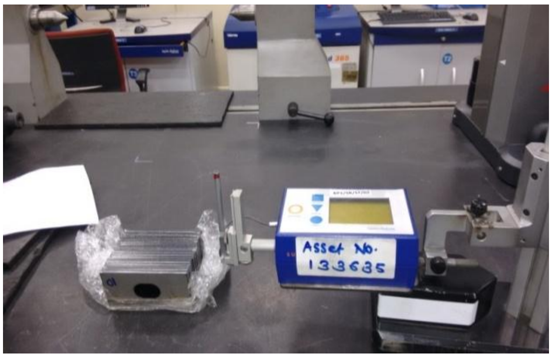

Figure 2 Surface roughness measurement

2.3 Design of Experiments

The design of experiment (DOE) was based on Taguchi Method of orthogonal array. Considering four factors, one at two levels and remaining at three levels each, Taguchi's L18 array was used. The experimental results for material removal rate (MRR) and Surface roughness (SR) for each 18 runs are shown in Table3.These results were further used for finding optimum parameters by using grey relational analysis technique as well as to determine contribution of parameters using ANOVA.

Table 2 Parameter level and values

Process Parameter	Level 1	Level 2	Level 3
Nozzle Diameter(mm)	1.2	2.0	-
Gas Pressure(MPa)	0.12	0.14	0.16
Cutting Speed (mm/min.)	2300	2500	2700
Cutting Power(W)	1800	1900	2000

III.GREY RELATIONAL ANALYSIS

Grey relational analysis implies that system having no information represented by black and system having all information represented by white but the grey system is that having information in between black and white. When experiments are complex or when the experimental method cannot be carried out exactly, grey analysis helps to make up for the shortcomings in statistical regression. Grey relation analysis is an effective means of

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analysing the relation in between the sequences with less data and can analyze many factors that can overcome the disadvantages of statistical methods (Ulas Caydas et. al. 2008). Procedure of grey relational analysis is described as follows:

Table 3 Observations for L18 Experimentation

Run No.	Nozzle Diameter (mm)	Gas Pressure (MPa)	Cutting Speed (mm/min)	Cutting Power (W)	Surface Roughness (Ra in µm)	Material Removal Rate (gm/min.)
1	1	1	1	1	1.69	34.5030
2	1	2	1	2	2.11	28.5437
3	1	3	1	3	1.89	24.2399
4	1	1	2	1	2.14	16.2466
5	1	2	2	2	1.34	15.7482
6	1	3	2	3	1.82	14.1399
7	1	2	3	1	1.64	9.5568
8	1	3	3	2	1.72	8.8584
9	1	1	3	3	2.34	14.1399
10	2	3	1	1	2.14	40.1388
11	2	1	1	2	1.94	32.4808
12	2	2	1	3	1.78	27.2699
13	2	2	2	1	1.86	22.9365
14	2	3	2	2	2.33	21.6538
15	2	1	2	3	2.42	24.2399
16	2	3	3	1	2.38	21.9808
17	2	1	3	2	1.97	20.6696
18	2	2	3	3	1.86	20.1999

3.1 Data pre-processing

In grey relational analysis if factors, goals and directions are different then method might produce incorrect results. Therefore pre-processing of the data is required and it is called as "grey relational generation". It is process of transferring original values to comparable values. For this purpose results obtained are normalised between zero and one. If there are m alternatives and n attributes, the i^{th} run can be expressed as y_{ij} =

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($y_{i1}, y_{i2}, y_{i3}, ..., y_{ij}$), where y_{ij} is the performance value of attribute j of run i. The term y_i can be translated into the comparability sequence x_{ij} = ($x_{i1}, x_{i2}, ... x_{ij}$), by use of one of Eq. 3 or 4

For smaller the better attributes:

$$X_{ij} = \frac{\max y_{ij} - y_{ij}}{\max y_{ij} - \min y_{ij}} \quad \text{for } i=1,2,.....,m \;\; j=1,2,...,n \qquad (3)$$

For larger the better attributes:

$$X_{ij} = \frac{y_{ij} - \min y_{ij}}{\max y_{ij} - \min y_{ij}} \quad \text{for } i=1,2,....,m \; j=1,2,...n \qquad (4)$$

In this study surface roughness (SR) is smaller the better attribute and material removal (MRR) rate is larger the better attribute. For example in case of SR smaller value is 1.34 µm from run no.5 and 2.42 µm is larger value from run no 15. By using equation no.3 normalised value for run no. 15 is (2.42-2.42)/(2.42-1.34)=0. For all runs are normalised values are given in Table 4.

Table 3 Results of grey relational generating, grey relational coefficient and grade

Run no.	Normalised value for SR (Ra)	Normalised value for MRR	Grey relational coefficient for SR(Ra)	Grey relational coefficient for MRR	Grey relational grade (w1=w2=0.5)
1	0.6759	0.8198	0.6067	0.7351	0.6709
2	0.2870	0.6293	0.4122	0.5743	0.4932
3	0.4907	0.4917	0.4954	0.4959	0.4957
4	0.2593	0.2362	0.4030	0.3956	0.3993
5	1.0000	0.2203	1.0000	0.3907	0.6954
6	0.5556	0.1688	0.5294	0.3756	0.4525
7	0.7222	0.0223	0.6429	0.3384	0.4906
8	0.6481	0.0000	0.5870	0.3333	0.4601
9	0.0741	0.1688	0.3506	0.3756	0.3631
10	0.2593	1.0000	0.4030	1.0000	**0.7015**
11	0.4444	0.7552	0.4737	0.6713	0.5725
12	0.5926	0.5886	0.5510	0.5486	0.5498
13	0.5185	0.4501	0.5094	0.4762	0.4928
14	0.0833	0.4091	0.3529	0.4583	0.4056
15	0.0000	0.4917	0.3333	0.4959	0.4146
16	0.0370	0.4195	0.3418	0.4628	0.4023

17	0.4167	0.3776	0.4615	0.4455	0.4535
18	0.5185	0.3626	0.5094	0.4396	0.4745

3.2 Grey relational coefficient

After data pre processing grey relational coefficient is to be measured. Grey relational coefficient is measured to express relationship between actual and ideal experimental results. Grey relation coefficient $\xi_i(k)$ for the K^{th} attribute in the i^{th} run can be determined by equation 5.

$$\xi_i(k) = \frac{\Delta_{min}+\zeta\Delta_{max}}{\Delta_{0i}(k)+\zeta\Delta_{max}} \qquad (5)$$

Where, Δ_{0i} is the deviation sequence

ζ is distinguishing or identification coefficient: ζ ϵ [0,1] (the value may be adjusted based on the actual system needs). A value of ζ is the smaller and the distinguished ability is the larger. ζ=0.5 is generally used. By calculating Δ_{0i}, Δ_{min} , Δ_{max} all grey relational coefficients can be calculated from equation 5. For example for run no. 1 $\Delta_{01}(1) = ||1 - 0.6759|| = 0.3241$ Δ_{min} =0 and Δ_{max}=1, if ζ=0.5 then $\xi_1(1) = (0 + 0.5 \times 1)/(0.3241 + 0.5 * 1)$=0.6067. Grey relational coefficients for all the runs are given in column 4 and 5 of Table 4.

3.3 Grey relational grade calculation

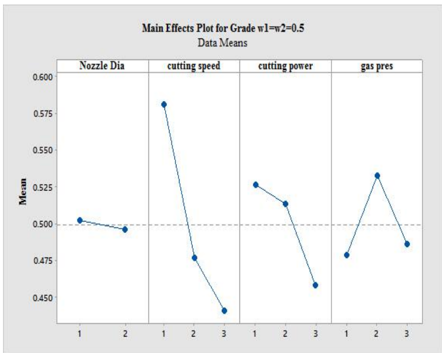
After the calculation of the entire grey relational coefficient $\xi_i(k)$, the grey relational grade γ_i calculated using Eq. (6)

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n} w_k \xi_i(k) \qquad (6)$$

Thus, the weights w_k of the two performance attributes were the same (50% each). By using Eq. (6), the grey relational grade can be calculated, for example in experiment no. 1 grade is $\gamma_i = (0.5 \times 0.6067 + 0.5 \times 0.7351) = 0.6709$ and for other experiments grades are shown in column 6 of Table 4.

IV.RESULTS AND DISCUSSION

After applying GRA technique it is observed that run no. 10 is having highest value of grey relational grade. Thus experiment no. 10 yields the best multi-performance characteristics for LBC process among the 18 experiments. Thus predicted optimum laser cutting parameter settings by GRA optimization technique for better performance characteristic should like nozzle diameter at 2.0 mm, cutting speed at 2300 mm/min, cutting power at 1800 watt and gas pressure at 0.16MPa. Main effect plot for grey relational grade and factors is shown in figure 3.



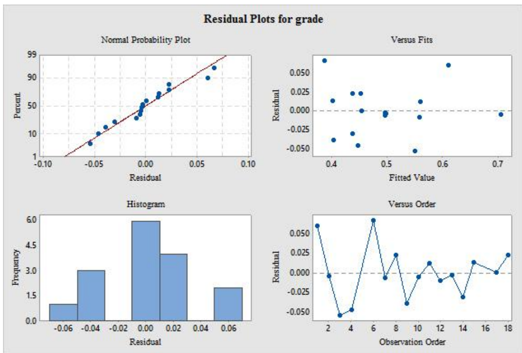


Figure 3 Response graph of LBC parameters Figure 4 Residual plot for grade

Table 4 ANOVA table

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Nozzle Dia.	1	0.011045	0.011045	5.11	0.054
Cutting Speed	2	0.075191	0.037595	17.40	0.001
Cutting Power	2	0.032082	0.016041	7.42	0.015
Gas Pressure	2	0.005641	0.002821	1.31	0.323
Error	8	0.017289	0.002161		
Total	15	0.128728			
S=0.0464876 R-sq=86.57% R-sq(adj)=74.82%					

ANOVA is performed on grey relational grade by using statistical software MINITAB 17 after applying grey relational analysis technique to find out the significant process parameters. Residual plot is also obtained and is as shown in figure 4. The reason to perform the ANOVA is to investigate which parameters of laser beam cutting process affect significantly on the performance characteristics. This can be achieved by separating the total variability of the grey relational grades. Table 5 gives the results of the ANOVA for performance characteristic using the values of grey relational grade. Table 5 indicates that the p-value of cutting speed and cutting power is less than 0.05 that represents significant effect of these two parameter on the performance characteristics. From F-value we can also find significant parameter i.e. larger the F-value more is the significance and vice-versa.

V. CONCLUSION

The Grey-Taguchi method with L18 array suggests the optimum setting of laser cutting parameters at nozzle diameter 2.0 mm, cutting speed 2300 mm/min, cutting power 1800 watt and gas pressure 0.16 MPa with equal weights for surface roughness and MRR for multiperformance. These optimal parameters were set and the confirmatory experiments performed. Surface roughness and MRR are measured for these experiments, average values found as 2.14 µm and 40.1388 mm/min respectively.

From the ANOVA results for grades shown in Table 5 with the help p-values we can find cutting speed and cutting power are significant as they are having p-value less than 0.05. F-value for cutting speed is 17.40 hence it is most significant and for cutting power it is 7.42 so that it is comparatively less significant. It seems that GRA is a straight forwarded method for optimizing performance characteristic problems in laser beam cutting.

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