Optimization of Machining Parameters in CW CO_2 Laser Cutting for Reduced Kerf Angle and Surface Roughness

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Abstract
Hot Rolled micro alloy steels (E34) find wide application in automotive sector. They are high quality steels having a blend of all the alluring properties that are not feasible in ordinary mild steel. These steels possess high yield strength, high notch toughness, good fatigue properties, excellent weld ability and better formability. E34 material finds application in construction of ships, railway wagons and carriages, pressure vessels, pipes, heavy duty transport vehicles, earth moving equipment and capacity tanks. The present study reports the application of non-contact type (thermal energy based) continuous wave (CW) CO_2 laser cutting process on Hot Rolled micro alloy steels (E34). The process parameters in laser cutting influence the kerf angle and surface roughness. These quality characteristics were observed for the various combinations of cutting parameters like cutting speed, beam power, assist gas pressure, focal length and standoff distance. Experiments were designed using central composite design method of Response surface technology. A significant improvement in the kerf angle and surface roughness was observed with the optimal setting of parameters.

Keywords: *Laser cutting, E34, Kerf angle, Surface roughness, Response surface method.*

INTRODUCTION

Laser beam machining (LBM) is one of the most widely used thermal energy based non-contact type advanced machining process which can be used to machine wide range of material. Adalarasan R et al. in 2015stated that in laser machining, the intense beam of laser melts the material thereafter it burns followed by vaporization of material, this vaporized material is then finally blown away by pressurized stream of gas thereby getting an edge with high cut quality [2,3]. Dubey AK, Yadava V in 2008 found that it is very much suitable for cutting geometrically complex profile and for making miniature holes in sheet metal [12]. Now-a-days, for avoiding delays in cost and time industries are strict with respect to the quality of cut/machined surface. Laser cutting is commonly used machining process for cutting various grades of steel mainly because of its cutting speed and machining cost while cutting sheet metals. There are two modes in laser cutting pulsed and continuous mode out of which continuous mode laser cutting is a renowned process in industries for cutting majority of materials such as metals, wood, magnetic sheets, depron foam, paper, rubber, ceramics and various composites. Recent advancements also suggest use of laser for micro-machining of components [4]. Lasers are broadly classified by the type of lasing material they use such as solid state crystal, semiconductor, dye, ionized gas, molecular gas, fiber laser. Out of these CO_2 lasers are widely used in industries as they produce high power at low cost. Due to these characteristics CO_2 laser is extensively used to cut flat steel sheets, and the present work is attracted by the inspiration to discover optimum input process parameters for Marathwada Auto Cluster, Aurangabad to cut E34 steel sheet. A. Riveiro et al. in 2011 investigated laser cutting on aluminum alloys and found for obtaining good surface finish argon gas is best for aluminum copper alloys, nitrogen for stainless steel and oxygen for carbon steel [1]. Ahmet Hasc-alık and Mustafa Ay in 2013 checked laser cut quality of difficult to cut Inconel 718 nickel based super alloy and found that cutting speed effect on surface roughness and kerf tapper ratio higher than laser power [6]. Scintilla LD et al. in 2013 stated that titanium alloys require high laser power for cutting with good surface finish [26]. Biswas R et al. in 2010 stated that choosing appropriate laser cutting machine and process parameters play key role in obtaining required quality characteristics [10]. A comparative study was done on Nd:YAG laser cutting of steel and stainless steel by K.H. Lo suggest that laser cut quality of continuous wave is better than sine and square wave [16]. Arun Kumar Pandey and Avinash Kumar Dubey in 2011 developed ANFIS model for kerf width and material removal rate and the same model was trained by using different experimental training data sets [9]. Suvradip Mullick et. al in 2016 investigated effect of laser incidence angle on cut quality of stainless steel and found that positive inclination yields better absorption qualities andbring down transmission loss and negative inclination applies uniform shearing type of force on the melt pool [31]. Anders Ivarsona in 2015 stated that silicon content does not affect cut edge quality, increased manganese content reduces cut edge quality and increased carbon content improves cut edge quality although manganese content is high, after studying influence of alloying elements on laser cutting process [8]. Aghdeab SH et al. in 2015 experimented laser cutting on aluminum alloy using regression modeling and simulated technique. This combined model gave best set of process parameters [5]. Yang CB et al. in 2012 was successful in creating a neural network which was effective in predicting process responses. [33]. Santhanakumar M et al. in 2016 stated that response surface method is most effective to predict process output precisely [25]. According to Sivarao S et al. in 2014 usually, before using RSM design of experiment is produced using central composite design [29]. Further, Al-Sulaiman et al. in 2009 proposed that found that assist gas pressure is significant process parameter that affects quality of laser cut. [7]. Yan et al. in 2013 used CO_2 laser cutting on alumina obtaining striation and crack free cut surfaces [32].

Form the extensive literature survey it was seen that study on quality characteristics for E34 material was not conducted and hence it was needed to find the optimum values to cut E34 sheet material. The motivation of the research is that a continuous wave mode CO_2 laser beam machine is used in Marathwada Auto Cluster, Aurangabad and E34 steel sheet was newly introduced to the machine. The initial setting of parameters created large kerf angle and poor surface finish. A good surface finish and geometric dimension is essential if the component is to be further assembled with tolerance. Thus, the present research work explores the quality characteristics of hot rolled micro alloy steel (E34) by utilizing Research surface methodology model in continuous mode CO_2 Laser cutting.

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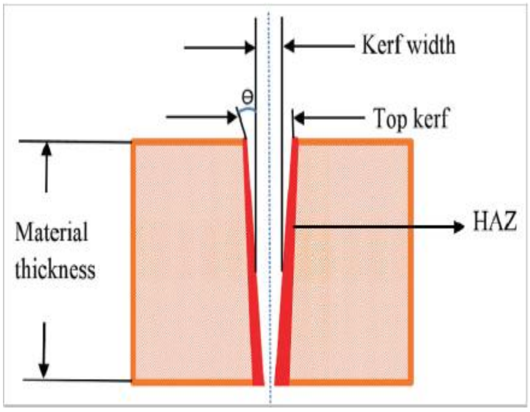


Fig: 1. *Laser cutting mechanics*

MATERIALS AND METHODS

Hot Rolled Micro alloy steel (E34) sheet

Hot Rolled micro alloy steels (E34) are high quality steels having a blend of all the alluring properties that are not feasible in ordinary mild steel. These steels possess high yield strength, high notch toughness, good fatigue properties, excellent weld ability and better formability. The table 1 below gives chemical properties. Due to these properties the material is being widely used as a substitute for normal mild steel.

Table: 1. *Chemical composition of E34 steel*

C	Mn	Si	S	P	Al	Nb	V	Ti
0.1	0.7	0.2	0.03	0.03	0.02	0.055	0.095	0.045

EXPERIMENTATION

The machine employed to carry out experimentation was DOMINO CP 4000. This is highly versatile laser machine: a single system can be used for flat parts 2D and 3D components processing and for bevel cutting and welding. It is a true 5-axis machine that cuts three dimensional pieces with any head orientation. Maximum laser power generated is 4000 W. The beam for current experimentation was focused to a spot using nozzle diameter of 1.5 mm; the direction of laser beam was kept at right angles to the workpiece for all the trials. A button hole cut of 10 mm length was made in each specimen to measure the kerf width on either side for kerf angle calculation. Since the laser beam machine worked in continuous wave mode, a square piece of 20 mm x 20 mm x 2.5 mm starting with a button hole cut was made. Fig 2 shows the profile pieces cut during experimentation.

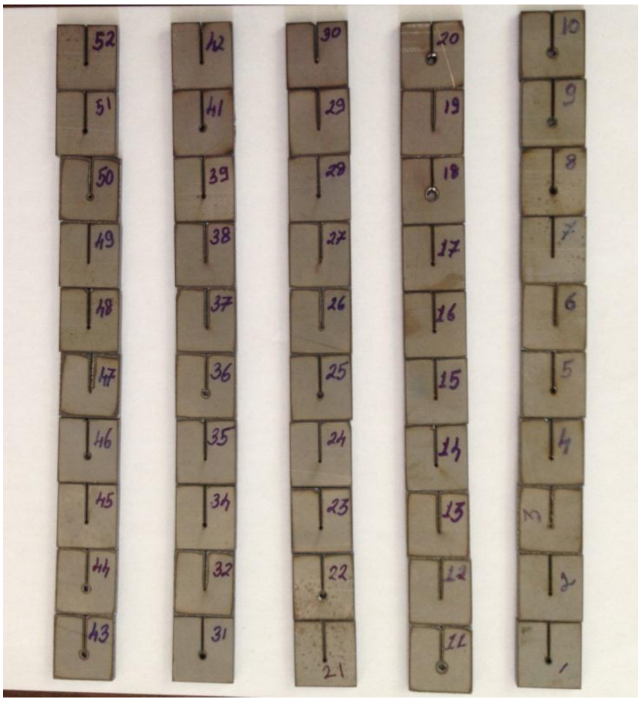


Fig: 2. *Profile cut for Experiments*

The process parameters considered for the current study were laser power, cutting speed, assist gas pressure, focal length and stand-off distance. Preparatory cutting trials were made to identify the range of selected parameters for minimum kerf width and dross formation along with reasonable surface finish. The selected parameters were varied between two levels (Table 2) and a two level full factorial Center Composite Design was used to conduct the cutting trials, which offers the detailed scope to study the interaction among parameters. The design of experiment was prepared considering 32 cube points, 10 center points in cube, 10 axial points and the value of α was kept at 2.37841.

Table: 2. *Levels of laser cutting parameters chosen for experimentation*

Cutting Parameters	Unit	Low level	High level
Laser power	W	2000	1000
Cutting speed	mm/s	2000	1000
Assist gas Pressure	Bar	0.8	1.6
Focal length	Mm	0.5	1.5
Stand-off distance	Mm	0.5	1.5

The cutting trials were executed on E34 sheet as per the designed profile cut. The measured output responses included the kerf angle and surface roughness. The kerf angle was measured using equation no.1

$$\text{Kerf Angle} = \frac{(Upper\ \text{kerf}\ width - Lower\ \text{kerf}\ width) \times 180}{2\pi t} \qquad (1)$$

Where t= thickness of sheet

A vision measuring machine MITUTOYO (OSL 2010) furnished with 2D measurement software was used to measure the kerf width on both sides as the average of the length of button hole cut. Surface Roughness was measured using MITUTOYO Surftest SJ-411 portable roughness tester and measurements were taken over the cut direction on the opposite side of button hole for a cut-off length of 12 mm. The observed characteristics are in table 3.

***Table: 3.** Response for various combinations of input parameters*

Std Order	Run Order	Pt Type	Blocks	Laser power (W)	Cutting speed (mm/min)	Assist gas pressure (bar)	Focal distance (mm)	Stand-off distance (mm)	Kerf angle (deg)	Surface roughness (µm)
42	1	-1	1	1500	1500	1.2	1	2.18921	1.18318	3.6
32	2	1	1	2000	2000	1.6	1.5	1.5	12.033	0.659
1	3	1	1	1000	1000	0.8	0.5	0.5	0.91605	10.491
10	4	1	1	2000	1000	0.8	1.5	0.5	6.18318	6.593
40	5	-1	1	1500	1500	1.2	2.18921	1	2.81605	3.601
24	6	1	1	2000	2000	1.6	0.5	1.5	12.1075	0.351
8	7	1	1	2000	2000	1.6	0.5	0.5	11.2967	0.611
3	8	1	1	1000	2000	0.8	0.5	0.5	6.88166	10.449
13	9	1	1	1000	1000	1.6	1.5	0.5	6.40102	0.494
25	10	1	1	1000	1000	0.8	1.5	1.5	1.02726	11.634
15	11	1	1	1000	2000	1.6	1.5	0.5	12.2357	0.459
51	12	0	1	1500	1500	1.2	1	1	2.35032	3.35
6	13	1	1	2000	1000	1.6	0.5	0.5	10.1901	0.269
12	14	1	1	2000	2000	0.8	1.5	0.5	10.6271	6.59
49	15	0	1	1500	1500	1.2	1	1	2.35032	3.35
44	16	0	1	1500	1500	1.2	1	1	2.35032	3.35
38	17	-1	1	1500	1500	2.15137	1	1	11.7163	0.585
7	18	1	1	1000	2000	1.6	0.5	0.5	11.9011	0.46
50	19	0	1	1500	1500	1.2	1	1	2.35032	3.35
11	20	1	1	1000	2000	0.8	1.5	0.5	7.90917	7.542
47	21	0	1	1500	1500	1.2	1	1	2.35032	3.35
9	22	1	1	1000	1000	0.8	1.5	0.5	1.27376	7.594
35	23	-1	1	1500	310.793	1.2	1	1	2.61656	0.57
4	24	1	1	2000	2000	0.8	0.5	0.5	10.7062	6.59
17	25	1	1	1000	1000	0.8	0.5	1.5	1.05248	7.532
41	26	-1	1	1500	1500	1.2	1	0.4	5.98369	4.383
39	27	-1	1	1500	1500	1.2	-0.1892	1	8.2921	4.378
36	28	-1	1	1500	2689.21	1.2	1	1	8.61656	4.53
18	29	1	1	2000	1000	0.8	0.5	1.5	7.37694	6.539
14	30	1	1	2000	1000	1.6	1.5	0.5	10.4331	0.556
23	31	1	1	1000	2000	1.6	0.5	1.5	11.7865	0.356
2	32	1	1	2000	1000	0.8	0.5	0.5	9.23248	6.47
52	33	0	1	1500	1500	1.2	1	1	2.35032	4.35
22	34	1	1	2000	1000	1.6	0.5	1.5	10.4217	0.579
5	35	1	1	1000	1000	1.6	0.5	0.5	6.20382	0.438
34	36	-1	1	2689.21	1500	1.2	1	1	12.2497	4.399
16	37	1	1	2000	2000	1.6	1.5	0.5	12.166	0.42
45	38	0	1	1500	1500	1.2	1	1	2.35032	4.35
19	39	1	1	1000	2000	0.8	0.5	1.5	6.9344	7.484
28	40	1	1	2000	2000	0.8	1.5	1.5	10.3265	6.532
29	41	1	1	1000	1000	1.6	1.5	1.5	7.32764	0.472
31	42	1	1	1000	2000	1.6	1.5	1.5	11.1706	0.473
46	43	0	1	1500	1500	1.2	1	1	2.35032	4.35
21	44	1	1	1000	1000	1.6	0.5	1.5	6.35401	0.467
26	45	1	1	2000	1000	0.8	1.5	1.5	7.12701	6.424
30	46	1	1	2000	1000	1.6	1.5	1.5	10.4217	0.542
20	47	1	1	2000	2000	0.8	0.5	1.5	10.282	6.569
27	48	1	1	1000	2000	0.8	1.5	1.5	7.24369	7.481
48	49	0	1	1500	1500	1.2	1	1	2.35032	4.35
43	50	0	1	1500	1500	1.2	1	1	2.35032	4.35

RSM

Response surface methodology explores the relation between various variables. It is a collection of various mathematical and statistical techniques which is further used to build empirical models. The RSM model is used to optimize output parameters that are controlled by various input parameters. If applied properly RSM model can maximize production rate. The advantages of this method over other methods include reduced cost of and their associated numerical noise. RSM grants the investigation of parameters impacts using 3D plots which are by and large impractical with different techniques.

Further, the study and investigation of output response (quality characteristics) curvature effects are possible with RSM, which has prompted its application in the present research work.

Table: 4. *Analysis of variance for kerf angle*

Source	Degree of freedom	Adj. Sum of squares	Adj. Mean Square	F-value	P-Value
Model	20	695.613	34.781	13.07	0
Linear	5	248.009	49.602	18.64	0
Laser power	1	135.497	135.497	50.93	0
Cutting speed	1	18.939	18.939	7.12	0.012
Assist Gas pressure	1	128.085	128.085	48.15	0
Focal distance	1	1.963	1.963	0.74	0.397
Stand-off distance	1	1.002	1.002	0.38	0.544
Square	5	256.282	51.256	19.27	0
Laser power*Laser power	1	85.164	85.164	32.01	0
Cutting speed*Cutting speed	1	38.116	38.116	14.33	0.001
Assist Gas pressure*Assist Gas pressure	1	71.884	71.884	27.02	0
Focal distance*Focal distance	1	37.093	37.093	13.94	0.001
Stand-off distance*Stand-off distance	1	11.975	11.975	4.5	0.043
2-Way Interaction	10	44.747	4.475	1.68	0.133
Laser power*Cutting speed	1	23.372	23.372	8.79	0.006
Laser power*Assist Gas pressure	1	16.436	16.436	6.18	0.019
Laser power*Focal distance	1	0.737	0.737	0.28	0.603
Laser power*Stand-off distance	1	0	0	0	0.993
Cutting speed*Assist Gas pressure	1	2.988	2.988	1.12	0.298
Cutting speed*Focal distance	1	0.355	0.355	0.13	0.718
Cutting speed*Stand-off distance	1	0.14	0.14	0.05	0.82
Assist Gas pressure*Focal distance	1	0.403	0.403	0.15	0.7
Assist Gas pressure*Stand-off distance	1	0.311	0.311	0.12	0.735
Focal distance*Stand-off distance	1	0.007	0.007	0	0.961

Regression Equation for kerf angle

Kerf angle = 13.98 - 0.0068 Laser power + 0.0005 Cutting speed - 12.25 Assist gas pressure
- 7.50 Focal distance- 4.54 Stand-off distance+ 9.48 Assist gas pressure*Assist gas pressure
+ 3.227 Focal distance*Focal distance+ 1.834 Stand-off distance*Stand-off distance
- 0.0035 Laser power*Assist gas pressure - 0.0006 Laser power*Focal distance
- 0.0015 Cutting speed*Assist gas pressure + 0.0004 Cutting speed*Focal distance
- 0.0002 Cutting speed*Stand-off distance + 0.56 Assist gas pressure*Focal distance
+ 0.49 Assist gas pressure*Stand-off distance+ 0.06 Focal distance*Stand-off distance (2)

Table:5. *Model Summary for kerf angle*

S	R-sq	R-sq(adj)	R-sq(pred)
1.63107	90.02 %	83.13 %	4.40 %

Table: 6. *Analysis of variance for surface roughness*

Source	Degree of freedom	Adj. Sum of squares	Adj. Mean Square	F-value	P-Value
Model	20	450.841	22.5421	21.45	0
Linear	5	61.65	12.3299	11.73	0
Laser power	1	0.131	0.1309	0.12	0.727
Cutting speed	1	1.852	1.852	1.76	0.195
Assist Gas pressure	1	57.108	57.1075	54.34	0
Focal distance	1	0.007	0.0069	0.01	0.936
Stand-off distance	1	0.001	0.0012	0	0.973
Square	5	24.239	4.8479	4.61	0.003
Laser power*Laser power	1	0.54	0.5396	0.51	0.479
Cutting speed*Cutting speed	1	5.351	5.3508	5.09	0.032
Assist Gas pressure*Assist Gas pressure	1	16.947	16.9465	16.12	0
Focal distance*Focal distance	1	0.154	0.1537	0.15	0.705

Stand-off distance*Stand-off distance	1	0.152	0.1517	0.14	0.707
2-Way Interaction	10	16.46	1.646	1.57	0.167
Laser power*Cutting speed	1	0.71	0.7104	0.68	0.418
Laser power*Assist Gas pressure	1	10.429	10.4287	9.92	0.004
Laser power*Focal distance	1	0.109	0.1088	0.1	0.75
Laser power*Stand-off distance	1	0.141	0.141	0.13	0.717
Cutting speed*Assist Gas pressure	1	0.503	0.503	0.48	0.495
Cutting speed*Focal distance	1	0.561	0.5613	0.53	0.471
Cutting speed*Stand-off distance	1	0.633	0.6328	0.6	0.444
Assist Gas pressure*Focal distance	1	0.162	0.1622	0.15	0.697
Assist Gas pressure*Stand-off distance	1	0.168	0.1676	0.16	0.693
Focal distance*Stand-off distance	1	3.044	3.0443	2.9	0.099

Regression Equation for surface roughness

Surface roughness = 29.15 - 0.0073 Laser power + 0.0034 Cutting speed
25.78 Assist gas pressure
- 0.94 Focal distance - 0.99 Stand-off distance + 4.60 Assist gas pressure*Assist gas pressure
- 0.208 Focal distance*Focal distance- 0.206 Stand-off distance*Stand-off distance
+ 0.0029 Laser power*Assist gas pressure + 0.0002 Laser power*Focal distance
+ 0.0003 Laser power*Stand-off distance + 0.0006 Cutting speed*Assist gas pressure
– 0.0005 Cutting speed*Focal distance - 0.0006 Cutting speed*Stand-off distance
+ 0.356 Assist gas pressure*Focal distance + 0.362 Assist gas pressure*Stand-off distance
+ 1.234 Focal distance*Stand-off distance (3)

Table:7. *Model Summary for surface roughness*

S	R-sq	R-sq(adj)	R-sq(pred)
1.02516	93.67 %	89.30 %	66.99 %

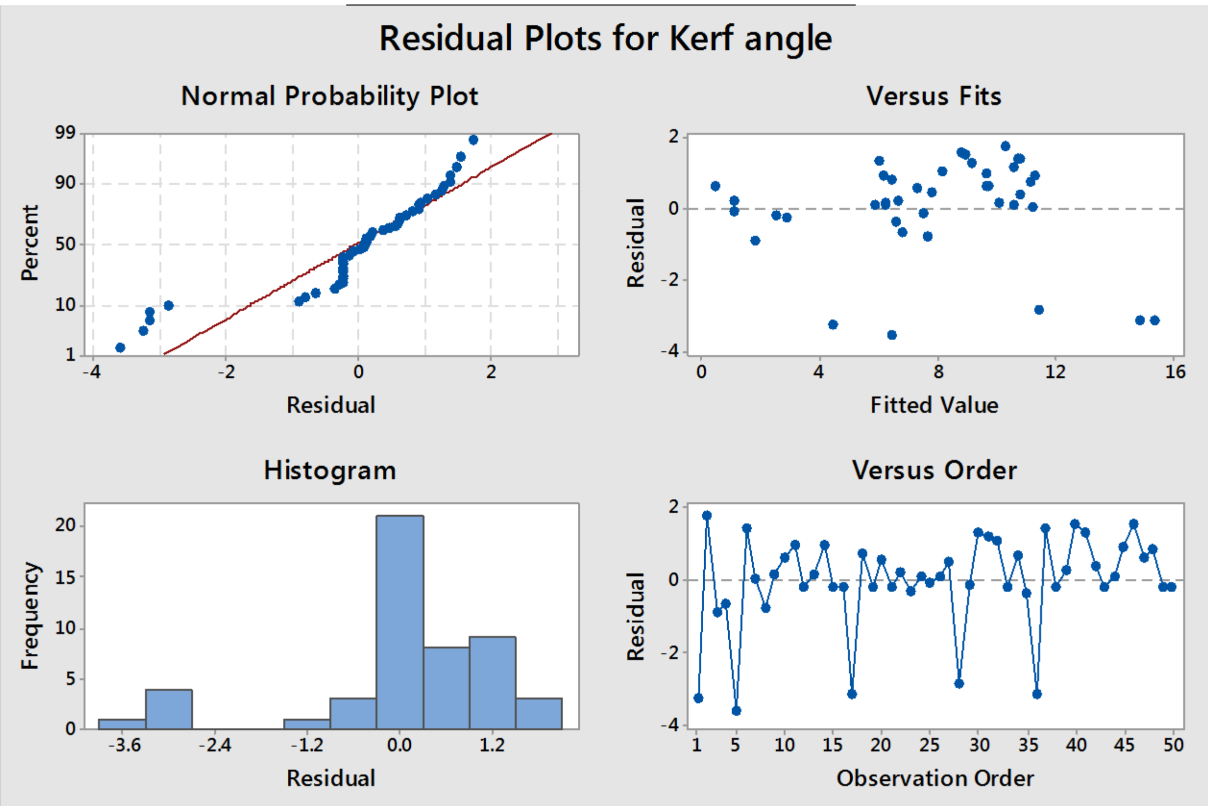


Fig: 3. *Residual Plot for kerf angle*

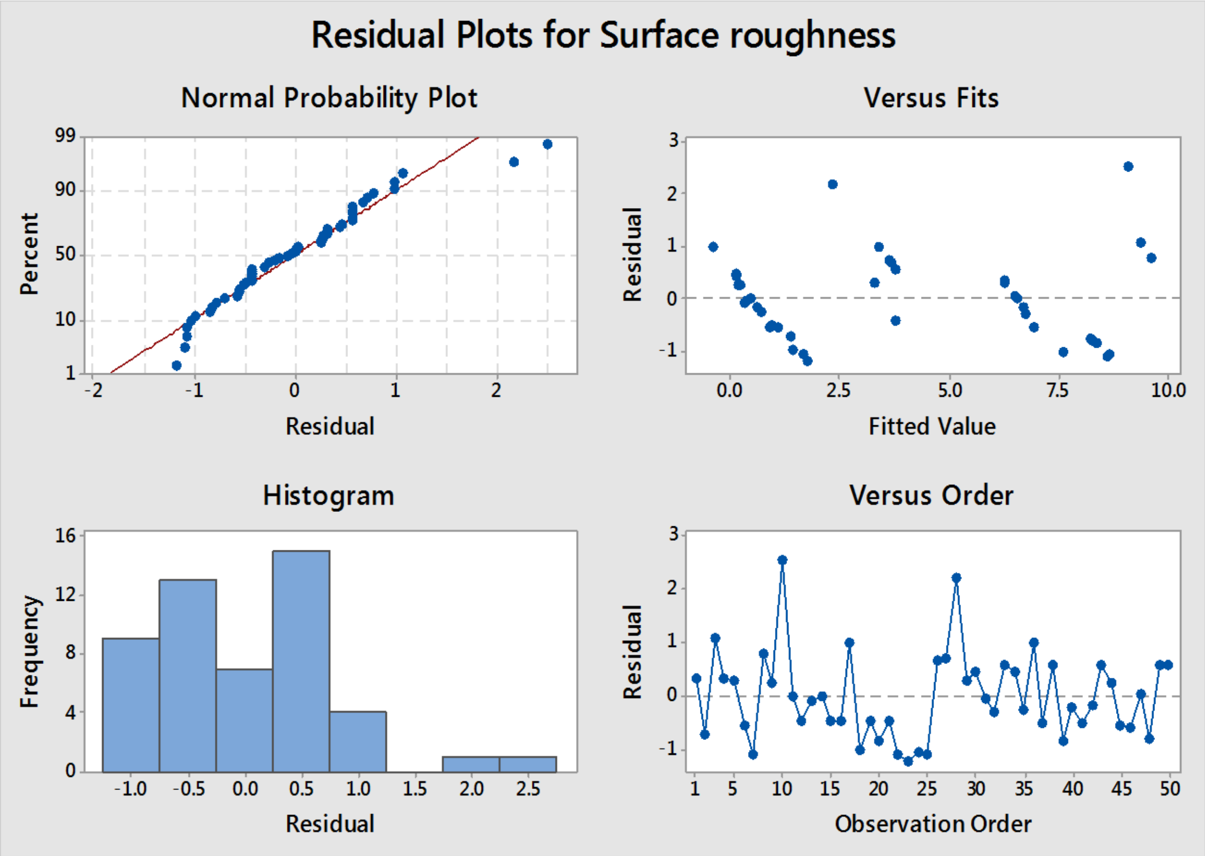


Fig: 4. *Residual Plot for surface roughness*

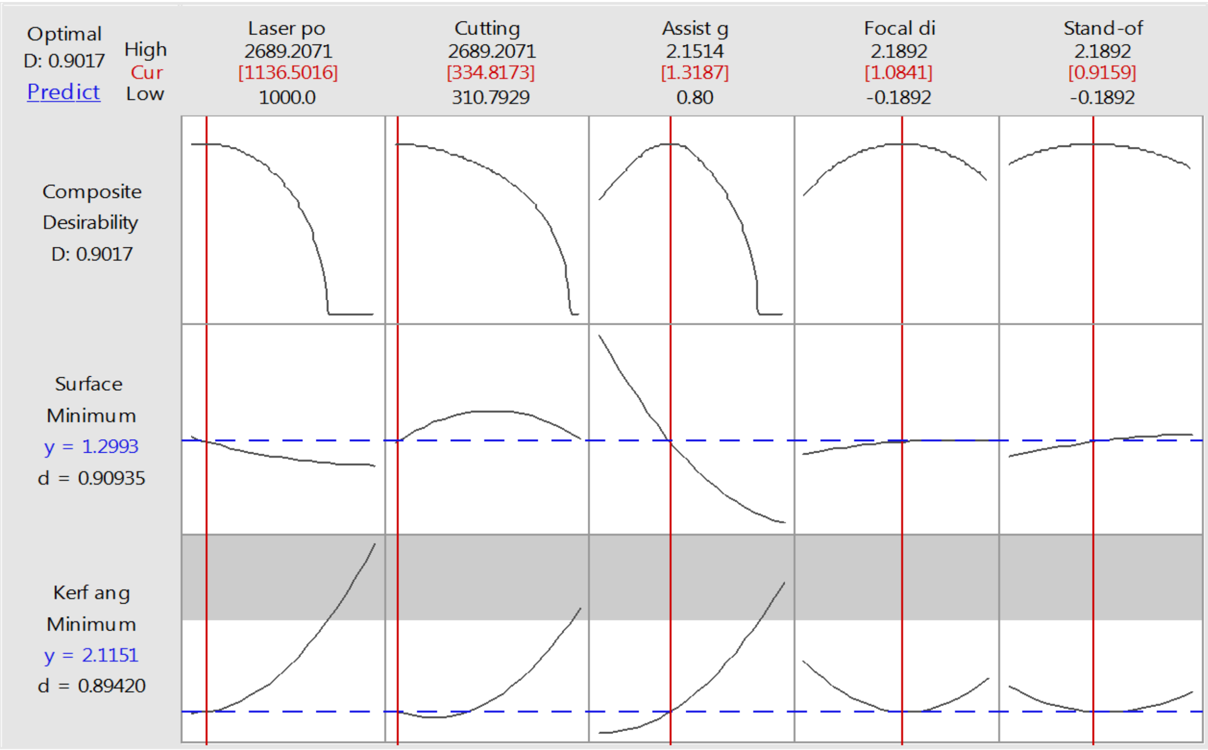


Fig: 5.*Optimization plot*

RESULTS AND DISCUSSION

RSM utilizes statistical method to analyze laser cutting process parameters and form polynomial equations of second order. The mathematical model which was created using RSM in Minitab 17 software counts the individual and consolidated impacts of laser cutting process parameters on both kerf angle (Eq.2) and Surface roughness (Eq.3). RSM's Center Composite Design was used for experimentation. The quadratic models are presented after eliminating the insignificant terms (Eq. 2and 3). The significant terms for kerf angle include cutting speed, cutting speed*cutting speed, Focal distance*Focal distance, Stand-off distance*Stand-off distance, Laser power*cutting speed, Laser power*Assist gas pressure whose probability was found to be less than 0.05 (Table 4) and cutting speed*cutting speed, Laser power*Assist gas pressure for surface roughness (Table 6). The R-squared values were found to be 90.02 % (Table 5) and 93.67 % (Table 7) their closeness to 100% describes the model fitness.

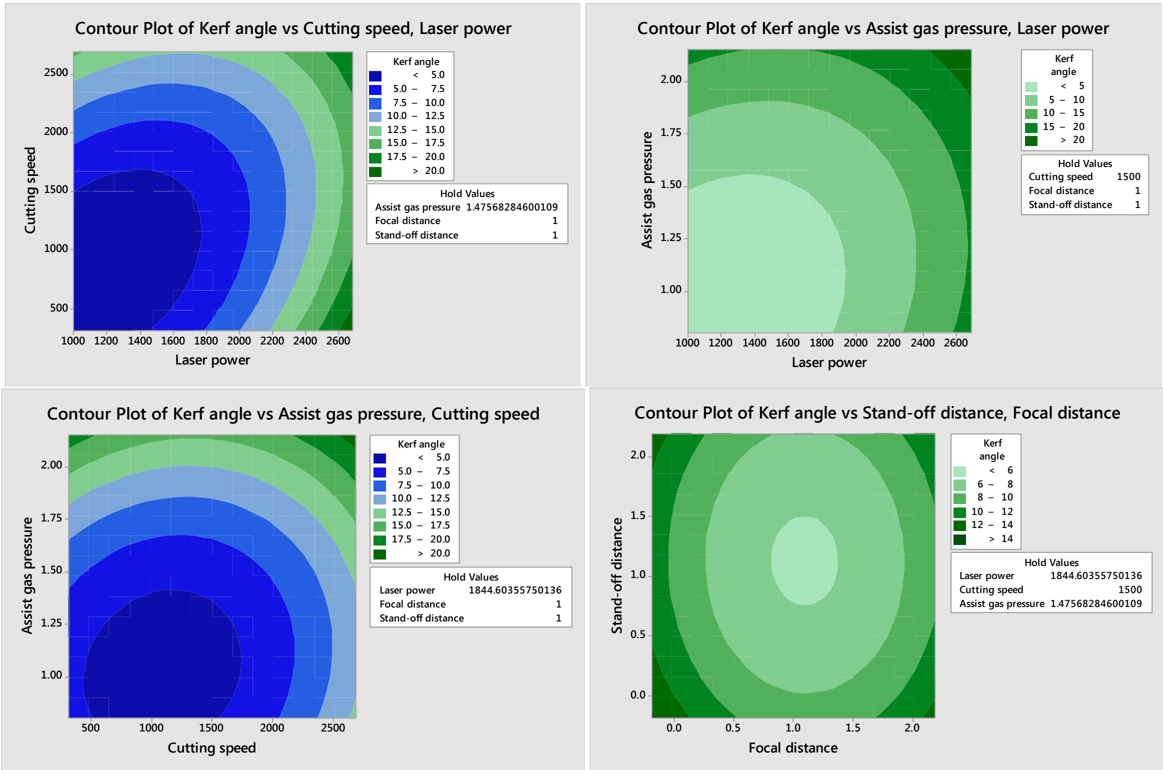
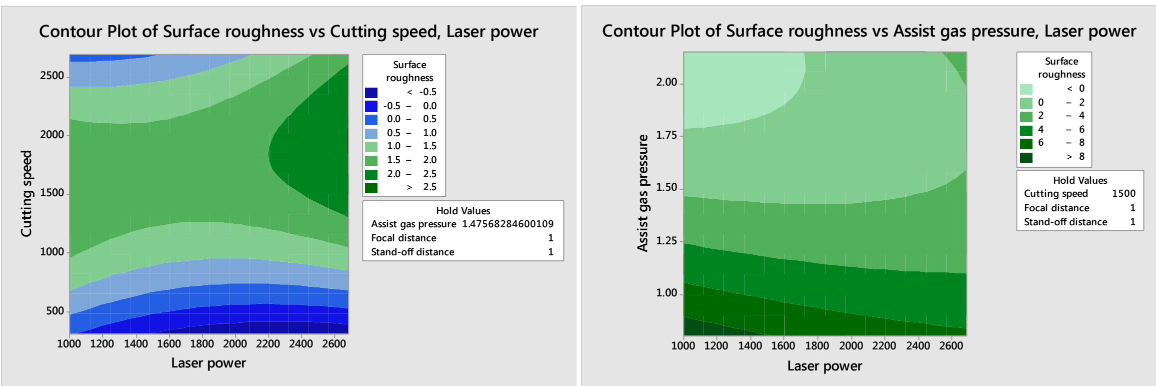


Fig: 6.*Contour plots for kerf angle*



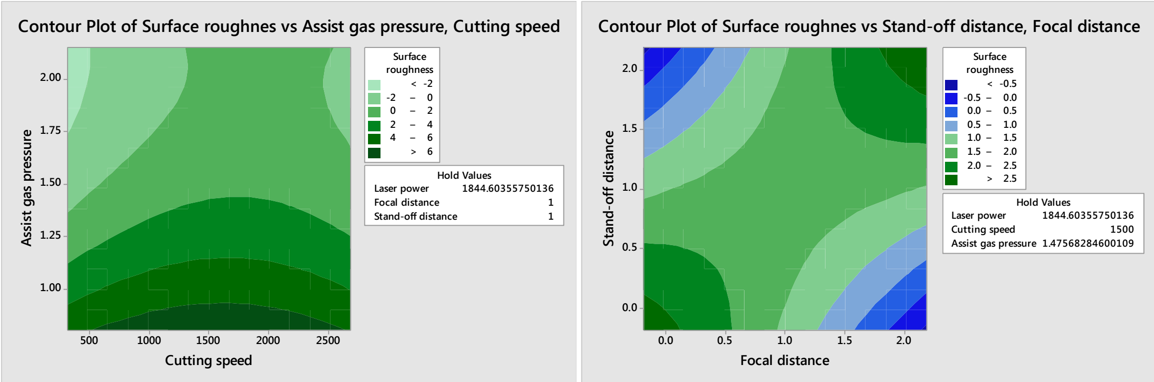


Fig:7. *Contour plots for surface roughness*

STUDY OF RESIDUAL PLOTS

Normal probability plot

This chart plots the residuals versus their expected values when the distribution is normal. The residuals from the investigation ought to be normally distributed. By and by, for adjusted or almost adjusted designs or for information with an extensive number of perceptions, moderate deviations from normality don't genuinely influence the outcome.

For kerf angle and surface roughness, the residuals generally appear to follow the straight line. Therefore, the given design is well balanced and no evidence of non-normality, skewness, outliers, or unidentified variables exists. Fig. 3 and 4 reveals that the residuals generally fall on a straight line, implying that the errors are normally distributed. This implies that the models proposed for kerf angle and surface roughness are adequate, and there is no reason to suspect any violation of the independence or constant variance assumption.

Residual versus fits

The graph in fig. 3 and fig. 4 shows residuals on y-axis and fitted values on x-axis. For both Kerf angle and surface roughness the residuals bounce randomly about 0-line showing that the assumptions that the relationship is linear are reasonable. The residuals roughly form a horizontal band along 0-line suggesting that the variances of the error terms are equal.

Residual versus frequency

This graph shows weather variance is normally distributed. A bell shaped histogram is distributed around zero indicating the assumptions are likely to be true.

Residual versus order plot

This graph plots the residuals in the order of the corresponding observations. This graph is thus used when the output may affect the results, which can happen when information is gathered in a period succession or in some other grouping for example geographic zone. This plot can be especially useful in an experimentation in which runs are planned.

The residuals in the plot ought to fluctuate in an irregular fashion across the line. Paying close attention to the plot shows whether there is any correlation between error terms. Connections among residuals might be shown by:

- An upward or downward pattern in the residuals
- Rapid changes in indications of adjacent residuals

For the given cycle time, the residuals appear to be randomly scattered about zero. Therefore, no evidence exists that the error terms are correlated with one another. Hence given model is accurately defined for laser cutting analysis.

OPTIMIZATION PLOT

Laser power

Increasing laser power kerf angle increases however surface roughness decreases. Hence optimal setting is in the lower of the range (1136.5016) because goal is to minimize both the responses. Vertical red line in the first column of graph represents optimal setting of laser power.

Cutting speed

By increasing cutting speed responses like kerf angle increases and surface roughness increases initially and later it was found to be decreasing. Therefore optimal setting is near the low level (334.8173). It was found that at low cutting speed quality characteristics found were better.

Assist gas pressure

Increasing assist gas pressure increases kerf angle and reduces surface roughness. Therefore the Assist gas pressure was found close to middle level (1.3187) in its optimal setting.

Focal length

Increasing focal length decreases kerf angle initially but does not affect much on surface roughness characteristics. Therefore the optimal setting for focal length is (1.0841) as shown by vertical red line.

Stand-off distance

Increasing stand-off distance, kerf angle initially decreases then increases however surface roughness slightly increases. Therefore the optimal setting for focal length is (0.9159).

CONCLUSION

The present research work is an investigation report on cut quality characteristics observed in continuous wave CO_2 laser cutting of hot rolled micro alloy steel (E34). Response surface methodology was used to create quadratic models for both kerf angle and surface roughness, and desirability analysis was applied to find out optimal values of laser cutting parameters. The quadratic model thus formed could be used to foresee the output values within the range of the operating parameters, and the examination discoveries will give a proper direction for continuous wave CO_2 laser cutting of E34 sheet. The experimentation was based on full factorization by center composite design unlike Taguchi's orthogonal array which includes reduced number of cutting trials. Usage of Center composite design in RSM was observed to help study the effect of parameters along their entire range, to identify the optimal continuous wave CO_2 laser cutting condition for E34 steel sheet as Laser power =1136.5016 W, Cutting speed=334.8173 mm/min, Assist gas pressure = 1.3187 bar, Focal length = 1.0841 mm and Stand-off distance = 0.9159 mm These optimum parameters were found to give best quality characteristics with kerf angle = 2.1151° and surface roughness = 1.2993µm.

1. A higher laser power produced high thermal energy which resulted in excessive melting of workpiece material thereby increasing kerf width as well as kerf angle.
2. A high assist gas pressure in combination with lower laser power effectively removed molten material from the cutting zone resulting in better surface finish.
3. As the cutting speed decreases kerf angle also decreases reason being lower cutting speed facilitated laser power to melt the material and pressurized gas to remove debris material effectively.
4. The interaction between laser power and cutting speed for kerf angle and laser power and assist gas pressure for surface roughness was found significant.
5. A lower laser power combined with

lower cutting speed and high assist gas pressure produced good cut characteristics.
6. RSM model produced was found to be fit mainly because the experimental values and predicted values for kerf angle and surface roughness synchronized very well.

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