Taguchi based multi-response optimization in CW CO_2 Laser Cutting Machine for Hot Rolled Micro Alloy steel (SS 4012A)

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Abstract: Hot Rolled micro alloy steels (SS 4012A) 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 posses high yield strength, high notch toughness, good fatigue properties, excellent weld ability and better formability. SS 4012A 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 (SS 4012A). The process parameters in laser cutting influence the kerf width 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 Taguchi's L_{27} orthogonal array and a hybrid approach of Response surface technology. A significant improvement in the kerf width and surface roughness was observed with the optimal setting of parameters.

Keywords: Laser cutting, SS 4012A, Kerf width, Surface roughness, Taguchi's L_{27} orthogonal array Response surface method

I. 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 and bring 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].

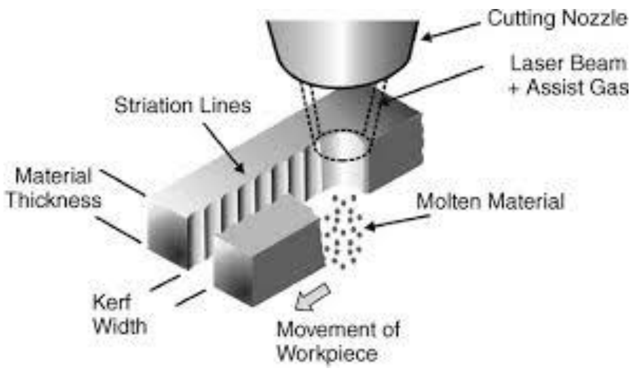

Figure 1: Laser cutting mechanics

Form the extensive literature survey it was seen that study on quality characteristics for SS 4012A material was not conducted and hence it was needed to find the optimum values to cut SS 4012A 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 SS 4012A steel sheet was newly introduced to the machine. The initial setting of parameters created large kerf width 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 (SS 4012A) by utilizing Research surface methodology model in continuous mode CO_2 Laser cutting.

II. COMPOSITION OF MATERIAL

Hot Rolled micro alloy steels (SS 4012A) are high quality steels having a blend of all the alluring properties that are not feasible in ordinary mild steel. These steels posses 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 SS 4012A 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

III. 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. 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 some sample profile pieces cut during experimentation.

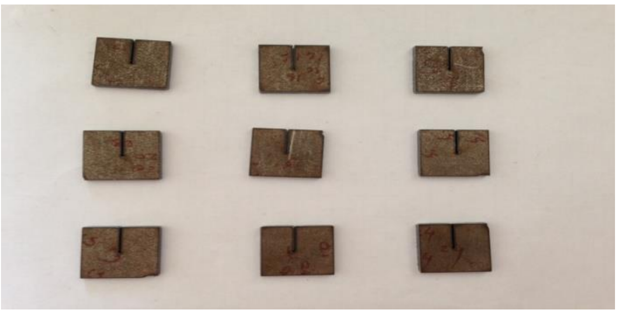

Figure 2: Profile cut for few Experiments

The process parameters considered for the current study were cutting speed, beam power, 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 among three levels (Table 2) and Taguchi's L_{27} Orthogonal array was used to conduct the cutting trials, which offers the detailed scope to study the interaction among parameters at minimum cost.

Table 2: Levels of laser cutting parameters chosen for experimentation

Cutting Parameters	Unit	Low level	Medium level	High level
Cutting speed	mm/min	1500	1750	2000
Beam Power	W	1100	1300	1500
Assist gas Pressure	bar	0.5	1	0.5
Focal length	mm	0.5	1	0.5
Standoff	mm	0.5	1	0.5

The cutting trials were executed on SS 4012A sheet as per the designed profile cut. The measured output responses included the kerf width and surface roughness. A vision measuring machine MITUTOYO (OSL 2010) furnished with 2D measurement software was used to measure the kerf. 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 at the half of sheet thicknesses, i.e. 1.25 mm from upper surface. The observed characteristics are in table 3.

Table 3: Response for various combinations of input parameters

Trial No.	Cutting speed (mm/min)	Beam power (W)	Gas pressure (bar)	Focal length (mm)	Stand off (mm)	Kerf width ($x10^{-1}$mm)	Surface roughness (µm)
1	1500	1100	0.5	0.5	0.5	4.210701	2.459
2	1500	1100	0.5	0.5	1	1.074268	3.535
3	1500	1100	0.5	0.5	1.5	5.671338	3.276
4	1500	1300	1	1	0.5	5.322803	3.792
5	1500	1300	1	1	1	2.143949	4.594
6	1500	1300	1	1	1.5	5.821529	6.12
7	1500	1500	1.5	1.5	0.5	8.751338	15.484
8	1500	1500	1.5	1.5	1	4.885987	11.499
9	1500	1500	1.5	1.5	1.5	5.61172	4.58
10	1750	1100	1	1.5	0.5	9.007516	3.334
11	1750	1100	1	1.5	1	4.827516	5.855
12	1750	1100	1	1.5	1.5	4.634904	5.096

13	1750	1300	1.5	0.5	0.5	4.513376	5.77
14	1750	1300	1.5	0.5	1	1.902038	7.198
15	1750	1300	1.5	0.5	1.5	2.89172	4.191
16	1750	1500	0.5	1	0.5	9.23707	4.623
17	1750	1500	0.5	1	1	4.133885	3.31
18	1750	1500	0.5	1	1.5	4.962803	5.091
19	2000	1100	1.5	1	0.5	4.249682	5.429
20	2000	1100	1.5	1	1	6.348917	4.307
21	2000	1100	1.5	1	1.5	4.622293	3.711
22	2000	1300	0.5	1.5	0.5	4.108408	2.622
23	2000	1300	0.5	1.5	1	1.416306	4.464
24	2000	1300	0.5	1.5	1.5	5.342293	5.735
25	2000	1500	1	0.5	0.5	12.16484	4.212
26	2000	1500	1	0.5	1	8.564713	2.811
27	2000	1500	1	0.5	1.5	12.96166	3.198

IV. RESPONSE SURFACE METHOD (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 width

Source	Degree of freedom	Adj. Sum of squares	Adj. Mean Square	F value	p Value
Model	14	192.137	13.7241	4.99	0.004
Linear	5	60.998	12.1995	4.44	0.016
Cutting speed	1	14.734	14.7343	5.36	0.039
Beam power	1	39.388	39.3884	14.32	0.003

Gas pressure	1	0.728	0.7280	0.26	0.616
Focal length	1	1.601	1.6013	0.58	0.460
Stand off	1	4.546	4.5456	1.65	0.223
Square	5	124.043	24.8085	9.02	0.001
Cutting speed*Cutting speed	1	2.262	2.2616	0.82	0.382
Beam power*Beam power	1	44.456	44.4563	16.17	0.002
Gas pressure*Gas pressure	1	40.846	40.8460	14.85	0.002
Focal length*Focal length	1	1.452	1.4520	0.53	0.481
Standoff*Stand off	1	35.027	35.0269	12.74	0.004
2-Way Interaction	4	7.097	1.7743	0.65	0.641
Cutting speed*Stand off	1	1.070	1.0702	0.39	0.544
Beam power*Stand off	1	1.386	1.3856	0.50	0.491
Gas pressure*Stand off	1	0.658	0.6575	0.24	0.634
Focal length*Stand off	1	3.984	3.9838	1.45	0.252

A. Regression Equation for kerf width

Kerf width = 131.2 - 0.0332 Cutting speed - 0.1661 Beam power + 22.21 Gas pressure - 2.23 Focal length- 16.9 Standoff + 0.000010 Cutting speed*Cutting speed + 0.000068 Beam power*Beam power 10.44 Gas pressure*Gas pressure + 1.97 Focal length*Focal length + 9.66 Standoff*Standoff+ 0.00239 Cutting speed*Standoff - 0.00340 Beam power*Standoff - 0.94 Gas pressure*Stand off - 2.30 Focal length*Standoff (1)

Table 5: Model Summary for kerf width

S	R-sq	R-sq (adj)	R-sq (paired)
1.65826	87.34%	68.24%	19.59%

Table 6: Analysis of variance for surface roughness

Source	Degree of freedom	Adj. Sum of squares	Adj. Mean Square	F value	p Value
Model	14	167.197	11.9426	4.84	0.005
Linear	5	107.466	21.4932	8.72	0.001
Cutting speed	1	19.740	19.7401	8.01	0.015
Beam power	1	17.614	17.6141	7.14	0.020
Gas pressure	1	40.662	40.6622	16.49	0.002
Focal length	1	26.935	26.9354	10.92	0.006
Stand off	1	4.546	4.5456	1.65	0.223
Square	5	11.245	2.2491	0.91	0.505
Cutting speed*Cutting speed	1	0.155	0.1549	0.06	0.806
Beam power*Beam power	1	0.149	0.1492	0.06	0.810
Gas pressure*Gas pressure	1	6.869	6.8694	2.79	0.121
Focal length*Focal length	1	3.308	3.3078	1.34	0.269
Stand off*Stand off	1	0.764	0.7640	0.31	0.588
2-Way Interaction	4	48.486	12.1215	4.92	0.014
Cutting speed*Stand off	1	5.522	5.5216	2.24	0.160
Beam power*Stand off	1	12.630	12.6301	5.12	0.043
Gas pressure*Stand off	1	28.827	28.8269	11.69	0.005
Focal length*Stand off	1	1.507	1.5073	0.61	0.449

B. Regression Equation for surface roughness

Surface roughness = 9.0 - 0.0186 Cutting speed + 0.0050 Beam power + 0.65 Gas pressure - 2.08 Focal length + 13.6 Standoff+ 0.000003 Cutting speed*Cutting speed + 4.28 Gas pressure*Gas pressure+ 2.97 Focal length*Focal length - 1.43 Standoff*Standoff + 0.00543 Cutting speed* Standoff - 0.01026 beam power*standoff - 6.20 gas pressure*standoff – 1.42 Focal length*standoff (2)

Table7: Model Summary for surface roughness

S	R-sq	R-sq (adj)	R-sq(pred)
1.57033	92.96%	67.42	0.00%

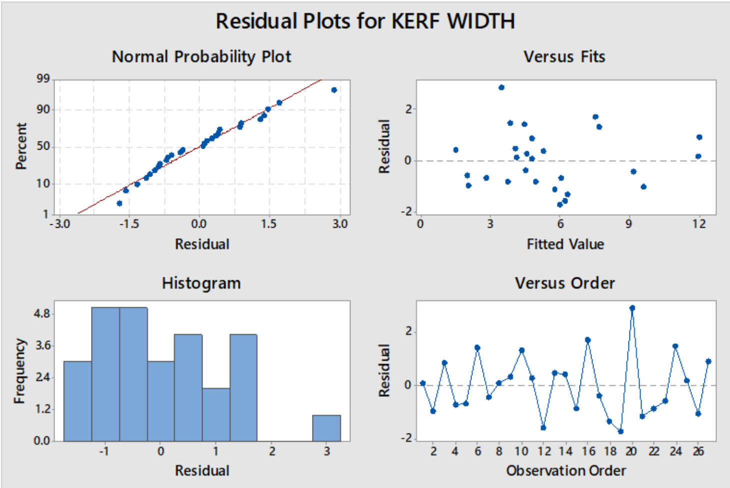

Figure 3: Residual Plot for kerf width

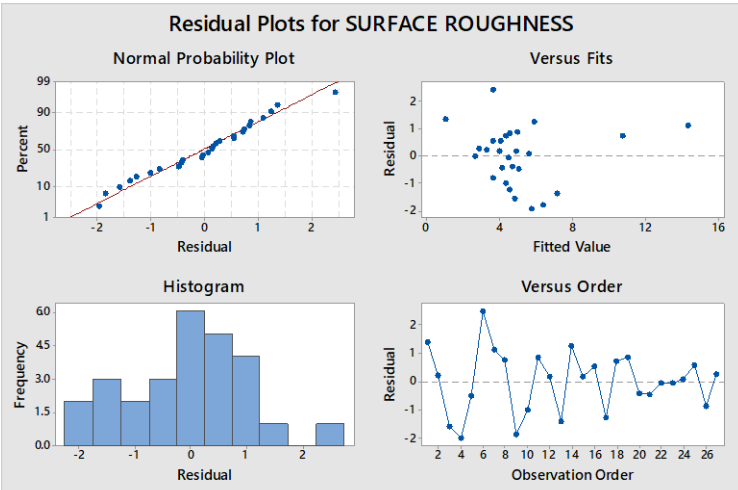

Figure 4: Residual Plot for surface roughness

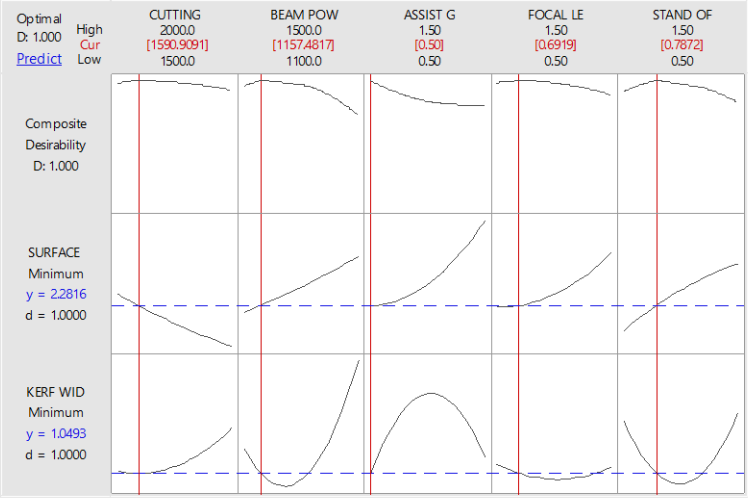

Figure 5: Optimization plot

V. RESULTS AND DISCUSSION

Before 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 width and Surface roughness. Taguchi's L_{27} orthogonal array was used for experimentation. The quadratic models are presented after eliminating the insignificant terms Eq. 1and 2). The significant terms for kerf width include cutting speed, beam power, Beam power*Beam power, Gas pressure*Gas pressure and Standoff*Standoff whose probability were found to be less than 0.05 (Table 4) and Cutting speed, Beam power, Gas pressure, Focal length, Beam power*Standoff, Gas pressure*Stand off for surface roughness (Table 6). The R-squared values were found to be 87.34% (Table 5) and 92.96 % (Table 7) their closeness to 100% describes the model fitness. The fitness of experimental data of the developed model for Kerf width was exhibited by the realistic agreement between the predicted R-squared (19.59%) and adjusted R-squared value (68.24 %) observed from Table 5. A similar observation was made for model related to Surface roughness as well.

I. STUDY OF RESEDUAL PLOTS

A. ***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 width 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 width and surface roughness are adequate, and there is no reason to suspect any violation of the independence or constant variance assumption.

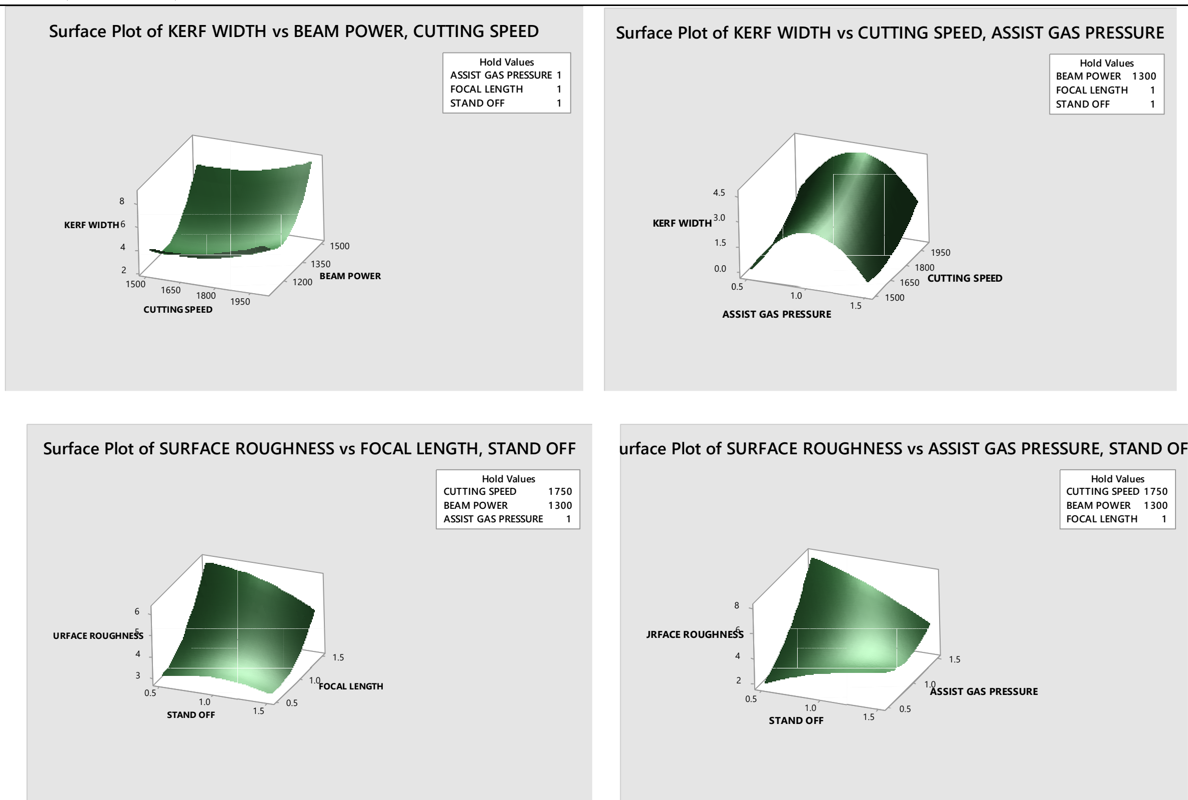

Figure 6: Response surface plots for kerf width and surface roughness

B. ***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 width 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.

C. ***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.

D. ***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 [37].

II. 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 (SS4012A).Taguchi based Response surface methodology was used to create quadratic models for both kerf width 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 SS4012A sheet. The experimentation was based on Taguchi's L_{27} orthogonal array thus resulting in reduced experiment runs and cost. Taguchi based RSM approach was observed to be optimum to study the effect of parameters along their entire range and to identify the optimal continuous wave CO_2 laser cutting condition for SS 4012A steel sheet as Cutting speed=1590.9091 mm/min, Beam power =1157.4817 W, , Assist gas pressure = 0.5 bar, Focal length = 0.6919 mm and Stand-off distance = 0.7872mm. These optimum parameters were found to give best quality characteristics with minimum kerf width and minimum surface roughness.

- A lower level of beam power (1157.4817 W) was found to be just enough to melt the material and get the required cut resulting in minimum kerf width.
- A higher assist gas pressure was found to effectively remove excess of molten material thereby increasing kerf width.
- A lower cutting speed was found to produce spot overlapping resulting in a rough cut surface. Beam power in combination with cutting speed was found to be significant, and thus, a medium cutting speed (1590.9091 mm/min) with lower beam power (1157.4817 W) was found to produce quality cut characteristics.
- RSM model produced was found to be fit mainly because the experimental values and predicted values for kerf width and surface roughness synchronized very well.

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Ethical statement: The authors declare that they have followed ethical responsibilities.

REFERENCES

[1] A. Riveiro, F. Quintero, F. Lusquiños, R. Comesaña, J. del Val, J. Pou (2011), The Role of the Assist Gas Nature in Laser Cutting of Aluminum Alloys, Physics Procedia 12 558-554.

[2] Adalarasan R, Santhanakumar M (2015) Application of Taguchi based response surface method (trsm) for optimization of multi responses in drilling Al/SiC/Al2O3 hybrid composite. J Inst Eng (India): Series C 96(1):65–71.

[3] Adalarasan R, Santhanakumar M, Rajmohan M (2015) Optimization of laser cutting parameters for Al6061/SiCp/Al2O3 composite using grey based response surface methodology (GRSM). Measurement 73(1):596–606.

[4] Adalarasan R, Santhanakumar M, RajmohanM(2015) Application of Grey Taguchi-based response surface methodology (GT-RSM) for optimizing the plasma arc cutting parameters of 304L stainless steel. Int J Adv Manuf Technol 78(5–8):1161–1170.

[5] Aghdeab SH, Mohammed LA, Ubaid AM (2015) Optimization of CNC turning for aluminum alloy using simulated annealing method. Jordan J Mech Indl Eng 9(1):39 44.

[6] Ahmet Hasc-alık , Mustafa Ay (2013), CO2 laser cut quality of Inconel718 nickel–based superalloy, Optics and laser technology 48 554-564.

[7] Al-Sulaiman F, Yilbas BS, Ahsan M, Karatas C (2009) CO2 laser cutting of Kevlar laminate: influence of assisting gas pressure. Int J Adv Manuf Technol 45(1–2):62–70.

[8] Anders Ivarsona, John Powell, Jukka Siltanen (2015), Influence of alloying elements on the laser cutting process, 15th Nordic Laser Materials Processing Conference, Physics procedia 78 84-88.

[9] Arun Kumar Pandey and Avanish Kumar Dubey (2011), Intelligent Modeling of Laser Cutting of Thin Sheet, International Journal of Modeling and Optimization, 107-112.

[10] Biswas R, Kuar AS, Biswas SK, Mitra S (2010) Effects of process parameters on hole circularity and taper in pulsed Nd:YAG laser microdrilling of Tin-Al2O3 composites. Mater Manuf Process 25(6):503–514

[11] Ding H, Shin YC (2013) Improving machinability of high chromium wear-resistant materials via laser-assisted machining. Mach Sci Technol 17(2):246–269.

[12] Dubey AK, Yadava V (2008) Laser beam machining—a review. Int J MachTools Manuf 48(6):609–628

[13] Eltawahni HA, Rossini NS, Dassisti M, Alrashed K, Aldaham TA, Benyounis KY, Olabi AG (2013) Evaluation and optimization of laser cutting parameters for plywood materials. Opt Laser Eng 51(9):1029–1043.

[14] Gururaja S, Ramulu M, PedersenW(2013)Machining ofMMCs: a review. Mach Sci Technol 17(7):417

[15] Islam MU, Campbell G (1993) Laser machining of ceramics: a review. Mater Manuf Process 8(6):611–630

[16] K.H. Lo (2011), A comparative study was done on Nd:YAG laser cutting of steel and stainless steel using continuous, square and sine waveform, Journal of Materials Engineering and Performance, 21:907-914.

[17] Kalaimathi M, Venkatachalam G, Sivakumar M (2014) Experimental investigations on the electrochemical machining characteristics of monel 400 alloys and optimization of process parameters. Jordan J Mech Ind Eng 8(3):143–151.

[18] Karthikeyan R, Adalarasan R, Pai BC (2002) Optimization of machining characteristics for Al/SiCp composites using ANN/GA. J Mater Sci Technol 18(1):47–50.

[19] Kumpulainen T, Karjalainen I, Prusi T, Holsa J, Heikkila R, Tuokko R (2009) Pulsed laser machining implemented with piezoelectric actuator. Int J Optomechatronics 8(6):1–17

[20] Kurt M, Kaynak Y, Bagci E, Demirer H, Kurt M (2009) Dimensional analyses and surface quality of the laser cutting process for engineering plastics. Int J Adv Manuf Technol 41(3–4): 259–267.

[21] Lal S, Kumar S, Khan ZA, Siddiquee AN (2014) Wire electrical discharge machining of AA7075/SiC/Al2O3 hybrid composite fabricated by inert gas-assisted electromagnetic stir-casting process. J Braz Soc Mech Sci Eng 36(2):335–346.

[22] Lum KCP, Ng SL, Black I (2000) CO2 laser cutting of MDF: 1. determination of process parameter settings. Optics Laser Technol 42(1):67–76.

[23] Ren D, Narayan RJ, Lee Y (2009) Machined surface error analysis for laser micromachining of biocompatible polymers for medical devices manufacturing. Comput-Aided Design Appl 6(6):781–793

[24] Santhanakumar M, Adalarasan R, Rajmohan M (2015) Experimental modelling and analysis in abrasive waterjet cutting of ceramic tiles using grey-based response surface methodology. Arab J Sci Eng 40(11):3299–3311.

[25] Santhanakumar M, Adalarasan R, Rajmohan M (2016) Parameter design for cut surface characteristics in abrasive waterjet cutting of Al/SiC/Al2O3 composite using grey theory based RSM. J Mech Sci Technol 30(1):371–379.

[26] Scintilla LD, PalumboG, Sorgente D, Tricarico L (2013) Fiber laser cutting of Ti6Al4V sheets for subsequent welding operations: effect of cutting parameters on butt joints mechanical properties and strain behaviour. Mater Des 47:300–308.

[27] Sharma A, Yadava V (2011) Optimization of cut quality characteristics during Nd:YAG laser straight cutting of Ni-based super alloy thin sheet using grey relational analysis with entropy measurement. Mater Manufacturing Process 26(12):1522–1529.

[28] Shi A, Attia H, Vargas R, Tavakoli S (2008) Numerical and experimental investigation of laser-assisted machining of inconel 718. Mach Sci Technol 12(4):498–513.

[29] Sivarao S, Milkey KR, Samsudin ARN, Dubey AKN, Kidd PN (2014) Comparison between Taguchi method and response surface methodology (RSM) in modelling CO2 laser machining. Jordan J Mech nd Eng 8(1):35–42.

[30] Solaiyappan A, Mani K, Gopalan V (2014) Multi-objective for electrochemical machining of 6061Al/10%Wt Al2O3/5%Wt SiC composite using hybrid fuzzy-artificial bee colony algorithm. Jordan J Mech Ind Eng 8(5):323–331.

[31] Suvradip Mullick, Arpit Kumar Agrawal, Ashish Kumar Nath (2016), Effect of laser incidence angle on cut quality of 4 mm thick stainless steel sheet using fiber laser, Optics and laser technology 81 168-179.

[32] Yan Y, Ji L, Bao Y, Chen X, Jiang Y (2013) CO2 laser high-speed crack-free cutting of thick-section alumina based on close-piercing lapping technique. Int J Adv Manuf Technol 64(9–12):1611–1624.

[33] Yang CB, Deng CS, Chiang HL (2012) Combining the Taguchi method with artificial neural network to construct a prediction model of a CO2 laser cutting experiment. Int J Adv Manuf Technol 59(9–12):1103–1111.

[34] Yilbas BS, Akhtar SS (2011) Laser cutting of alloy steel: threedimensional modeling of temperature and stress fields. Mater Manuf Process 26(1):104–112.

[35] Yilbas BS, Akhtar SS, Karatas C (2013) Laser cutting of alumina tiles: heating and stress analysis. J Manuf Process 15(1):14–24.

[36] Yilbas BS, Khan S, Raza K, Keles O, Ubeyli M, Demir T, Karakas MS (2010) Laser cutting of 7050 Al alloy reinforced with Al2O3 and B4C composites. Int J Adv Manuf Technol 50(1–4):185–193.

[37] Himanshu .H. Deshmukh & Dr. Nitn .G. Phafat (2018) Optimization of Machining Parameters in CW CO2 Laser cutting for reduced kerf angle and Surface Roughness., Journal of Industrial Mechanics, 3(3): 34-46.

[38] Mayank Juneja, Nikhil Juneja, Anmol Bhatia (2018), Optimization of machining characteristics using CNC Lathe: A Critical review, International Journal of Advanced Engineering Research and Applications, Volume-4: 36-42.

This volume is dedicated to Late Sh. Ram Singh Phanden, father of Dr. Rakesh Kumar Phanden.

