Experimental Investigation and Analysis of Process Parameters in Laser Beam Machining of Aluminium Alloy 8011

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***Abstract*— Laser Laser beam machining is one of the nontraditional thermal energy based non contact type machining process where material removal takes place by melting and vaporization, is used for almost whole range of engineering materials. This study involves effect of laser power, cutting speed and assisting gas pressure on surface roughness and kerf width. Aluminum alloy 8011 is one of the difficult to cut material by laser beam machine because of its reflectivity. Because of its excellent properties it is widely used in electronic, space craft, military equipments. An aluminum alloy 8011 sheet of 3 mm thickness is used as workpiece material and nitrogen gas is used as assisting gas. The design of experiment plan is created by using Response Surface Methodology and analyzed by regression method. It is found that minimum surface roughness and kerf width can be obtained simultaneously by operating nearly at higher speed, lower power and gas pressure.**

Keywords*— *Laser Beam Machining, Surface Roughness, Kerf Width, Response Surface Methodology, ANOVA.

I. INTRODUCTION

The acronym “LASER” stands for Light Amplification by Simulated Emission of Radiation is a coherent and amplified beam of electromagnetic radiation. The key element in making a practical laser is the light amplification achieved by stimulated emission due to the incident photons of high energy. Laser comprises of three components namely lasing medium, lasing energy source and optical delivery or feedback system. The laser medium may be a solid, liquid or gas. Laser light differs from ordinary light because it has photons of same frequency, wavelength and phase, laser beams are highly directional, have high power density and better focusing characteristics. Among different types of lasers Nd:YAG and CO_2 are most widely used now a day’s [1], [2]. In this process material is removal by focusing highly intense laser beam on the work piece. The heat of the laser beam subsequently heats, melts and evaporates the work piece material, as this process does not need the cutting tool so no mechanical force is exerted on the work piece thus work piece does not need to be clamped like in conventional machining process [3].

Advanced sheet cutting processes (ASCPs) are well suited for cutting advanced difficult-to-cut materials (i.e. superalloys). Laser beam cutting process is one of the advanced sheet cutting processes, most widely used for generating complex profiles and geometries in almost all engineering materials. Though highly reflective materials such as aluminum and copper are not well suitable for cutting with laser beam, with proper beam control these materials can be cut satisfactorily [1]. In the competitiveness world market in metal processing industry, it is necessary to meet most stringent demands in terms of increased productivity, accuracy, quality of machined surface, reducing the consumption of materials and energy. To achieve these objectives, there is a broader use of technology of laser cutting of various materials [2].

A. Principle of Laser Beam Machining

The mechanism of material removal during includes different stages such as absorption and heating, melting, vaporization and chemical degradation. When a high energy density laser beam is focused on work surface the thermal energy is absorbed which heats and transforms the work volume in to a molten, vaporized or chemically changed state that can easily be removed by flow of high pressure assisting gas jet [4].

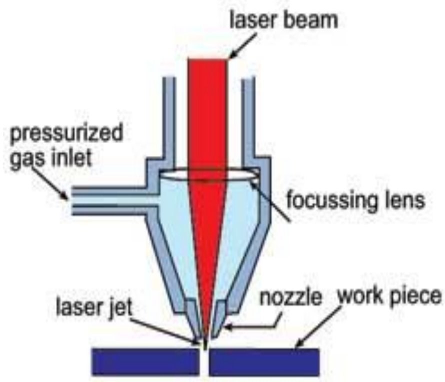

Fig 1. Principle of Laser Beam Machining

II. LITERATURE SURVEY

The primarily used lasers are Continuous Wave (CW) CO2 and pulsed Nd:YAG. The performance of laser beam machine depends on process parameters, material parameters and important performance characteristics are HAZ (Heat Affected Zone), Kw (kerf Width), Ra (Surface Roughness), recast layer. Regression analysis is not useful for precisely describing the non linear complex relationship between process parameters and performance characteristics For modeling and optimization of laser beam machining mostly taguchi method is used, but this methods will not provide an adequate model and response surface methods and artificial intelligence based models are capable to provide adequate model with multiple objectives[1]. The increase in power leads to increase in surface roughness, kerf width and reduction in cut quality if gas pressure is not changed, the surface roughness decreases and heat affected zone increases with increase in gas pressure because of increase in interaction time between beam and material faster the cutting and smaller energy density leads to lesser surface roughness, increase in pulse power and pulse frequency results in higher surface roughness and heat affected zone with almost all having linear relationship. Among the main variables controlling the process, the assist gas type is an essential factor [3]. In CO_2 laser cutting of a 2024-T3 aluminium-copper alloy found that Oxygen, nitrogen and compressed air react to a greater or lesser extent with the molten material generating a large amount of oxides and nitrides. This largely affects the cutting speed and cut quality of the obtained cuts. On the other hand, argon is the more efficient assisting gas to obtain best quality results with higher efficiency [5]. During cutting of mild steel of 6 mm thickness by laser cutting using L-27 orthogonal array and Response Surface Methodology (RSM) for parametric analysis found that surface roughness is directly proportional to duty cycle and frequency and inversely proportional to cutting speed. The effect of cutting speed, duty cycle and square of duty cycle on surface roughness were more as compared to frequency [6]. The roughness is highly affected by cutting speed and duty cycle even when it comes to interaction between cutting speed, frequency and duty cycle. The statistical analysis showed that a best surface roughness is obtained by operating at higher cutting speed with lower duty cycle regardless of frequency used [7]. Kerf width and heat-affected zone are mostly affected by laser power and cutting speed, greater values of laser power, in combination with lower values of cutting speed leads to more heat insertition in processing area per unit time which leads to extended dimensions of kerf width and heat-affected zone. The pulsing frequency and assist gas pressure play an important role on the morphology of the cutting surface. Lower values of the pulsing frequency, with same speed will result in decreasing laser spot overlaps and increases the undulations on the cutting edge surface [8]. In the work of [9], Obtained mathematical models showed good dependence of surface roughness and width of heat affected zone on varied process parameters. To obtain smaller roughness one should aim at greatest possible cutting speed and least gas pressure, small variation of gas pressure has no significant effect on cutting process. Cutting speed has inverse relationship with thickness of material to be cut. With increasing laser power more energy is transferred to work material resulting in increase in heat affected zone and decreases with increase in cutting speed. Gas pressure has very little effect on heat affected zone because pressurized gas is used to eject the molten metal over surface resulting extra heating so heat affected zone will decreases [10]. P.J. Pawar and G.B. Rayate given the effective range of assist gas pressure, cutting speed, laser power and pulse frequency to achieve minimum kerf width, kerf taper and surface finish [11]. RSM is more promising due to its giving very low average error towards modelling and experimental validation. The desirability criteria helps user to determine the optimum conditions and significance of interactions and square terms can be clearly predicted. Surface plot of RSM revealed that cutting speed is the most significant factor in minimizing kerf width followed by laser power. Though both Taguchi technique and RSM techniques predicted near values of average error, the RSM technique seems to be more promising in predicting response via mathematical modelling over Taguchi technique [12]. Design of Experiments is a tool for determining significance of different variables affecting the process quality and calculating optimal configuration for controlling factors. While designing or optimizing any product with DOE methods, it is very important to select proper method. RSM is less expensive than traditional methods, by this method the objective function can be easily solved and considerable amount of time and computation can be saved. For small number of variables with few levels full factorial method is good but when variable increases it becomes tedious [13].

III. PROPOSED METHODOLOGY

In this paper, modelling of Ra and Kw using RSM is perceived. RSM is selected to map the experiments with a reduced number of trial runs to effectuate optimum responses. The discrete feature of RSM is used extensively in the industrial world to examine and characterize problems in which input variables influence some performance aspect of the product or process. This performance measure is called the response. Models developed by RSM were subsequently used for optimization.

In the existing work, the optimization problem of LBM was undeniably framed as a multi-objective optimization problem for the determination of the optimal machining conditions between Ra and Kw. It can be noted that the classical optimization methods are not efficacious for handling multi-objective optimization problems because they do not find multiple solutions in a single run, and therefore it is necessary for them to be applied as many times as the number of desired Pareto-optimal solutions. The above-mentioned difficulty of classical optimization methods is eliminated in response surface methodology. RSM based multi-objective optimization methodologies have been widely used in the literature to find Pareto-optimal solutions.

IV. MODELLING AND OPTIMIZATION USING RSM

RSM is collection of mathematical and statistical techniques used for modeling and analysis of the problem in which objective function to be optimized is affected by the several variables. The response surface methodology comprises regression surface fitting to obtain approximate responses, design of experiments to obtain minimum variances of the responses and optimizations using the approximated responses [6].

It is designed to develop a mathematical relationship relating the controllable parameters to the experimental responses. It is used to examine the relationship between one or more response variables and a set of quantitative experimental variables or factors. These methods are often employed after identifying a “vital few” controllable factors to find the factor settings that optimize the response [7].

Response surface methods involves following steps:

a) The experimenter needs to move from the present operating conditions to the vicinity of the operating conditions where the response is optimum. This is done using the method of steepest ascent in the case of maximizing the response and the method of steepest descent in case of minimizing the response.

b) Once in the vicinity of the optimum response the experimenter enters, he needs to fit a more elaborate model between the response and the factors. Special experiment designs referred to as RSM designs and are used to accomplish this. The fitted model is used to identify the best operating conditions.

c) It is possible that a number of responses may have to be optimized at the same time. The optimum settings for each of the responses in such cases may lead to conflicting settings for the factors. A balanced setting has to be found that gives the most appropriate values for all the responses. Desirability functions are useful in these cases [14].

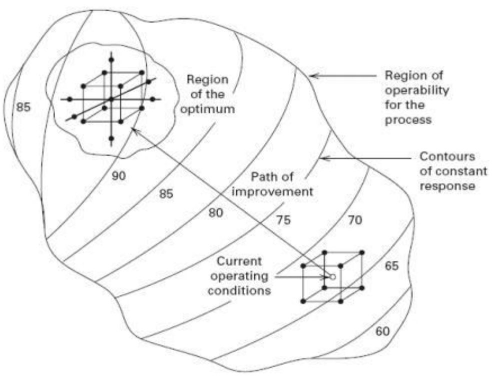

Fig 2 Sequential nature of RSM

Minitab helps to create RSM design of experiment plan. When user defines the levels of input parameters, then Minitab creates a plan based on input parameters, plan creates middle level when first level and last level are given, by their own by considering the difference between input values.

V. EXPERIMENTAL DETAILS

The investigation of experiments was enforced with CO_2 laser beam system (Model: TLC1000) delivering maximum peak power of 15 kw. The experimental set up of laser cutting process was shown in Fig. 3. The output laser beam was focused by a plano-convex lens whose focal distance is 127 mm. The fixed conditions at which the experiments were conducted are listed in Table 1.

Fig 3. Laser Beam Machining Setup

TABLE 1. Cutting Conditions

1	Workpiece material and Thickness	Aluminium alloy 8011 of 3 mm thickness
2	Focal length	127 mm
3	Nozzle diameter	1.4 mm
4	Type of gas	N_2
5	Gating frequency	10000 Hz
6	Nominal output power	2 Kw
7	Emission wavelength	1080 nm

The work material used for the current analysis is Aluminum alloy 8011 and the chemical composition is given in Table 2. The work material used for the current analysis was Al8011 with cutting dimensions of 40*40 mm and 3 mm in thickness. Because of the large number of independent parameters that control the laser cutting process, some preliminary experiments were conducted in order to determine which parameters should be considered for optimization. The three control variables, viz. Laser Power, Cutting Speed and Gas Pressure each at three levels, and nozzle tip distance whose effect was unknown which has been taken in 2 blocks, were chosen. The different levels of the parameters used in the experimentation are shown in Table 3. It was decided to use three-level test for each factor since the determined factors were multi-level variables whose outcome effects were not linearly related. The levels were fixed based on detailed preliminary experiments. The two quality characteristics analyzed were surface roughness and kerf width.

TABLE 2. Chemical Composition of Aluminium alloy 8011

Elements	Al	Si	Cu	Fe	Mn	Mg	Cr
% Wt	98.57	0.52	0.08	0.62	0.17	0.01	0.01

TABLE 3. Cutting Parameters and levels

Sr. No	Level / Parameters	1	2	3
1	Laser Power (W)	1000	1200	1400
2	Cutting Speed (m/min)	0.8	1.0	1.2
3	Gas Pressure (Bar)	12	14	16

The Surface Roughness and Kerf width of each cut was measured at three different places for accurate evaluation. The Ra of laser cut surfaces was measured from centerline of the cut edge using a TIMR GROUP Inc.'s TR100 Portable Piezoelectric type Surface Roughness tester and Kw was measured by using PPT300 profile projector. The experiments were planned implementing the Box-Behnken Design with two blocks and a replication for the Design of Experiments (DOE) using MINITAB 17 software, which helped to minimize the number of experiments. The results for 30 experiments after laser beam cutting which were evaluated as stated earlier on two performance measures were shown in Table 4.

TABLE 4. Experimental Data

Run Order	Pt Type	Blocks	Cutting Speed (m/min)	Laser Power (W)	Gas Pressure (bar)	Ra (μm)	Kw (mm)
1	0	2	1	1200	14	7.83	0.205
2	2	2	1.2	1200	12	2.48	0.185
3	0	2	1	1200	14	5.91	0.205
4	2	2	0.8	1200	12	7.32	0.22
5	2	2	0.8	1400	14	6.43	0.265
6	2	2	1	1000	16	7.99	0.195
7	2	2	1	1000	12	4.8	0.175
8	2	2	1	1400	12	3.49	0.215
9	0	2	1	1200	14	6.37	0.21
10	2	2	0.8	1000	14	7.75	0.195
11	2	2	1	1400	16	12.13	0.235
12	2	2	0.8	1200	16	13.99	0.225
13	2	2	1.2	1400	14	5.41	0.205
14	2	2	1.2	1200	16	6.69	0.19
15	2	2	1.2	1000	14	5.38	0.195
16	2	1	1.2	1200	16	8.93	0.195
17	0	1	1	1200	14	6.31	0.195
18	2	1	1	1400	16	11.56	0.22
19	2	1	0.8	1200	16	13.82	0.24
20	2	1	0.8	1200	12	5.65	0.235
21	0	1	1	1200	14	6.49	0.205
22	2	1	1.2	1400	14	4.3	0.215
23	2	1	1.2	1000	14	3.79	0.165
24	2	1	1.2	1200	12	2.13	0.175
25	2	1	1	1000	16	9.07	0.18
26	0	1	1	1200	14	7.63	0.21
27	2	1	0.8	1000	14	10.79	0.215
28	2	1	1	1400	12	4.21	0.205
29	2	1	1	1000	12	3.15	0.185
30	2	1	0.8	1400	14	9.38	0.26

VI. DEVELOPMENT OF EMPERICL MODELS

Based on the Box-Behnken Design, experiments were conducted to develop empirical models for Ra and Kw in terms of three input variables. Values of various regression statistics were compared to identify best fit model. The need in developing the mathematical relationships was to correlate the machining responses to the cutting parameters thereby facilitating the optimization of the machining process. The statistical models based on the second-order polynomial quations formulated for Ra and Kw using the experimental details were given below:

Ra = 38.9 + 0.034 Block – 0.0198 Power –17.4 Speed -2.58 Gas Pressure - 0.000003 Power*Power + 11.78 Speed*Speed + 0.0996 Gas Pressure*Gas Pressure - 0.00151Power*Speed + 0.00215 Power*Gas Pressure – 1.197 Speed*Gas Pressure (1)

Kw = 0.045 – 0.00039 Block + 0.000084 Power - 0.345 Speed + 0.0368 Gas Pressure + 0.000000 Power*Power + 0.2435 Speed*Speed - 0.001653 Gas Pressure*Gas Pressure -0.000253 Power*Speed + 0.000006 Power*Gas Pressure + 0.00469 Speed*Gas Pressure (2)

Here the P values of speed, gas pressure were less than 0.05 for Ra and speed, power and gas pressure were less than 0.05 for Kw which are significant respectively at 95 % confidence level. The normal probability plots of the residuals for the output responses were shown in Figs. 4 and 5. An analysis on these plots affirms that the residuals were positioned on a straight line, which means that the errors were distributed consistently and the regression models were proportionately well fitted with the observed values. To check whether the fitted models actually interpret the experimental data, the multiple regression coefficients (R^2) were computed. The multiple R^2 for Ra and Kw were found to be 0.9081 and 0.9029 respectively. This shows that the second- order model can justify the variation in the Ra and Kw up to the measure of 90.81% and 90.29%, respectively. It can be said that the second-order models were adequate in representing the process on the basis of these values of the multiple regression coefficients.

TABLE 5. Analysis of Variance for Ra

Source	DF	Adj SS	Adj MS	F- Value	P- Value
Model	10	258.29	25.829	18.78	0.000
Linear	4	244.78	61.195	44.48	0.000
Speed	1	81.090	81.090	58.95	0.000
Gas Pressure	1	162.24	162.244	117.94	0.000
Error	19	26.137	1.376		
Lack-of-Fit	15	23.103	1.540	2.03	0.259
Pure Error	4	3.035	0.759		
Total	29	284.43			
S	R-sq		R-sq (adj)		
1.17288	90.81%		85.97%		

TABLE 6. Analysis of Variance for Kw

Source	DF	Adj SS	Adj MS	F- Value	P- Value
Model	10	0.013200	0.001320	20.08	0.000
Linear	4	0.009648	0.002412	36.70	0.000
Power	1	0.004728	0.004728	71.92	0.000
Speed	1	0.005231	0.005231	79.58	0.000
Gas Pressure	1	0.000452	0.000452	6.87	0.017
Error	18	0.001138	0.000066		
Lack-of-Fit	14	0.001050	0.000075	2.25	0.225
Pure Error	4	0.000133	0.000033		
Total	28	0.014383			
S		R-sq	R-sq (adj)		
0.0081075		91.77%	87.20%		

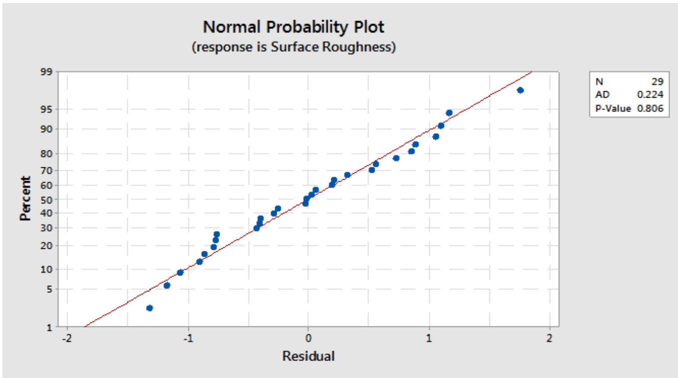

Fig 4. Normal Probability Plot of Ra

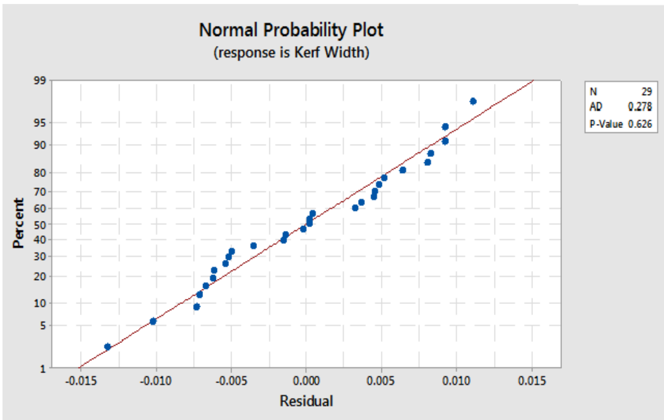

Fig 5. Normal Probability Plot of Kw

A. *Effect of process parameters on Ra*

As shown in Fig. 6, the speed and gas pressure are continuous variables and power is kept constant at 1000 W. The minimum Ra value occurs when the speed is high and gas pressure is low. The roughness value goes on increasing with increase in gas pressure and decrease in speed.

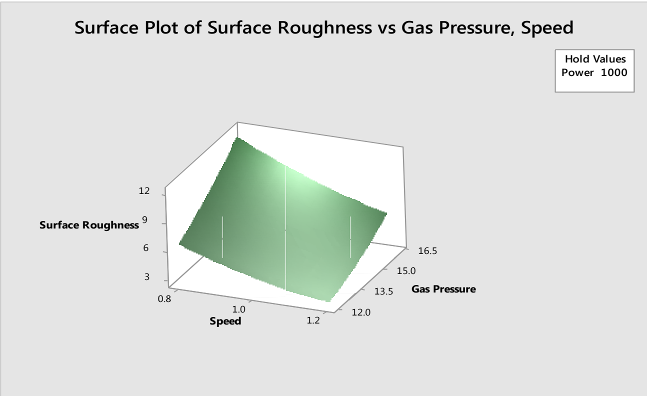

Fig 6. Surface plot of Ra vs Gas Pressure and Speed

The main effect plot Fig. 7 shows that the line for block seems to be parallel to X- axis; it means that the block is not affecting the response. The increase in speed decreases the roughness value, increase in gas pressure increases the roughness value and increase in power initially increases surface roughness and then slightly decreases. The gas pressure and speed significantly affects the surface roughness and power is less significant.

The interaction plot is shown in Fig. 8. Block vs power, block vs gas pressure, power vs gas pressure and power vs speed have cross interactions; hence these interactions have significance on Roughness value. The lines in block vs speed plot are overlapped. The speed vs gas pressure plot appears to be parallel so there is no evidence of an interaction between speed and gas pressure.

From the Pie Chart Fig. 9 we see that gas pressure have maximum contribution of 60.8% and speed have 33.5% contribution on roughness value and other parameters contribute at minimum level.

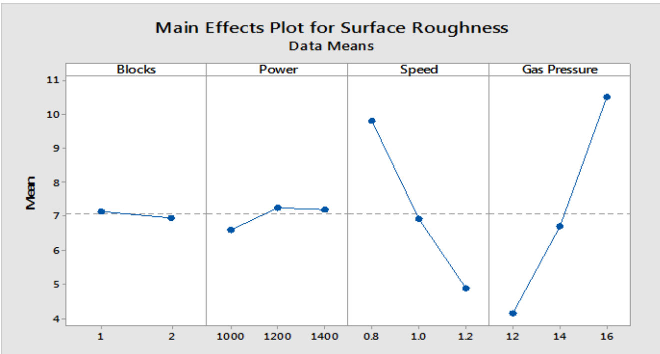

Fig 7. Main effect plot for Ra

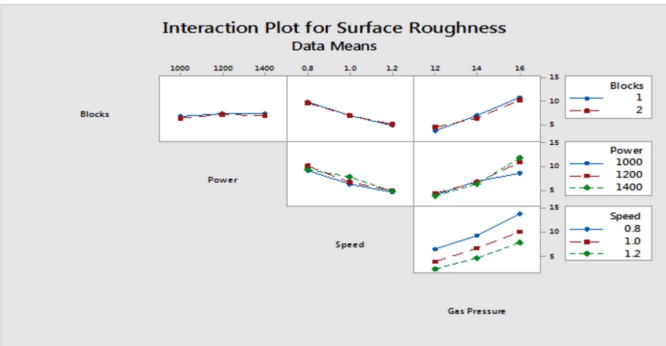

Fig 8. Interaction Plot for Ra

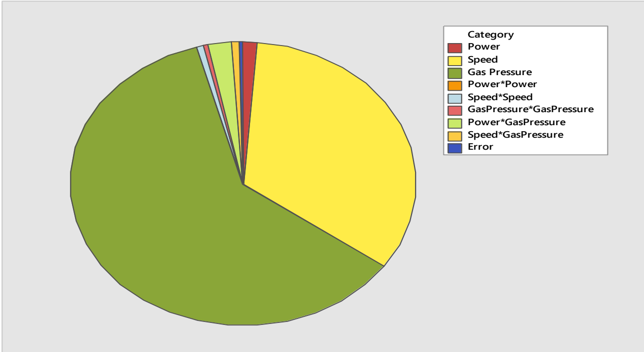

Fig 8. Pie Chart for Ra

B. *Effect of process parameters on Kw*

Here the speed and power are continuous variables and gas pressure is kept constant at 12 Bar. Response is kerf width. The plot shows how speed and power are related to the kerf width, the minimum kerf width occur when the speed is high and power is low. The kerf width goes on increasing with increase in power and decrease in speed as shown in Fig. 10.

The main effect plot Fig. 11 shows variation of individual responses for four parameters. All main effects are showing non linear relationship with response. The plot shows that the line for block seems to be parallel to the X- axis, it means that the block is not affecting the response. The increase in speed decreases the kerf width very fast in between 0.8 to 1.0 m/min speed and slowly between 1.0 to 1.2 m/min that of 0.8 to 1.0 m/min speed. Increase in power increases the kerf width and gas pressure increases the kerf width between 12 to 14 bar pressure and decreases kerf width between 14 to 16 bar gas pressure. The speed and power significantly affects the kerf width and effect of gas pressure is less significant.

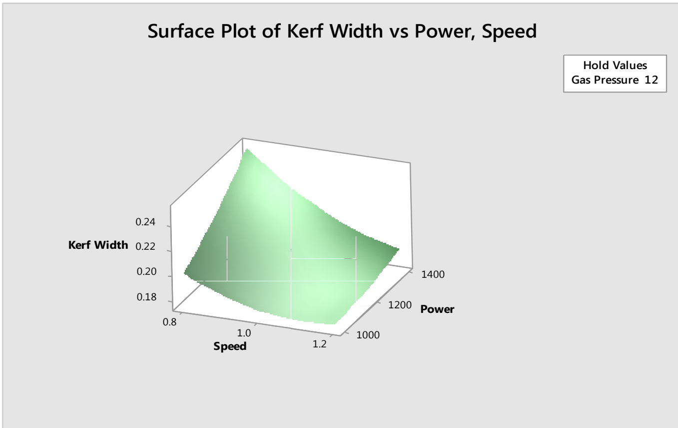

Fig 10: Surface plot of Kw vs Power and Speed

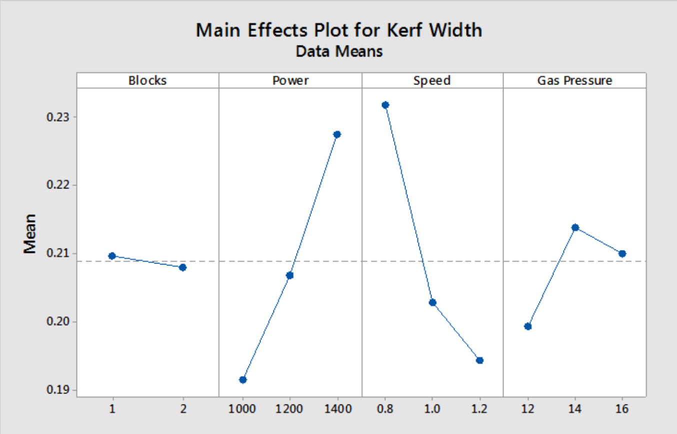

Fig 11: Main effect plot for Kw

The interaction plot Fig. 12 shows that, block vs power, block vs speed, block vs gas pressure and power vs gas pressure have cross interactions; hence these interactions have significance on kerf width. The plot of power vs speed don't have interaction at 1400 w power with other parameters and the plot of speed vs gas pressure don't have interaction at 0.8 m/min speed with other parameters That is, at these levels the effect of one of these process variables is not influenced by the other process variable on the response.

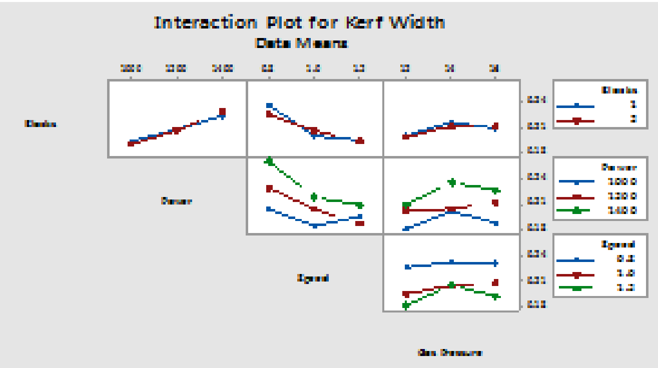

Fig 12: Interaction Plot for Kw

From the Pie chart Fig. 13. We see that speed contributes 42.7% and power 38.6% on roughness value and other parameters contribute at minimum level.

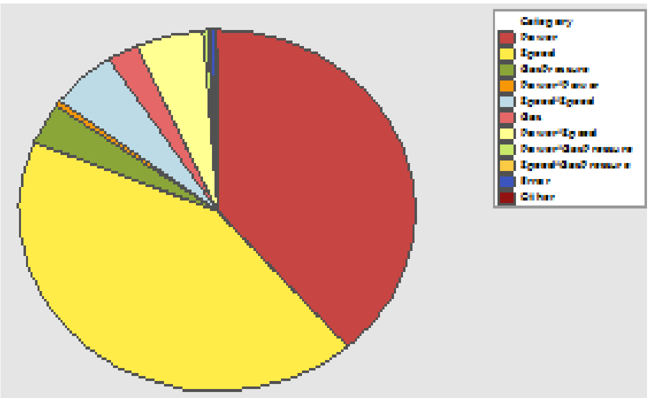

Fig 13: Pie Chart for Kw

VII. RESPONSE OPTIMIZATION

In the process of response optimization, the objective is to minimize both Ra and Kw. From the optimization plot Fig. 14. it is observed that surface roughness and kerf width shows individual desirability as 0.95808 and 0.94417 respectively. The minimum response values of Ra and Kw obtained are 2.63 µm and 0.1706 mm respectively. The composite desirability of 0.9511 is very good and indicates that all responses were close to their ideal settings. The response optimization had not produced a perfect composite desirability because both Ra and Kw had not achieved their ideal settings but they are within the acceptable range. The above values of Ra and Kw are achieved by setting speed at 1.1273 m/min, power at 1060.6061 W and gas pressure at 12.0 Bar.

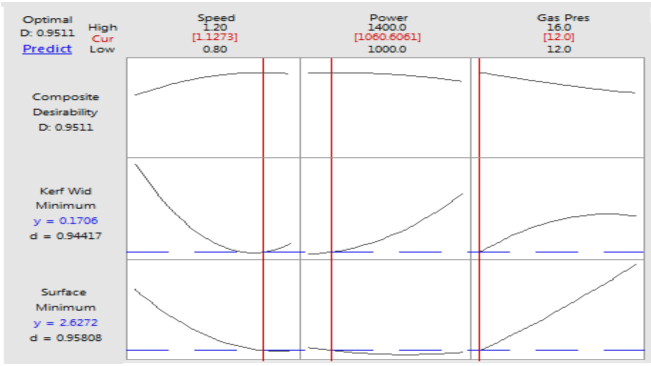

Fig 14: Optimization of Response parameters

VIII. CONCLUSION

The results obtained from the data analysis indicate that the power, cutting speed and gas pressure have significant effect on surface roughness and kerf width. The response surface model fits the experimental data of surface roughness well with coefficient of correlation nearing 93.73%, R-sq (adjusted) 90.25% and R-sq (predicted) 82.27% with insignificant lack of fit, and experimental data of kerf width well with coefficient of correlation nearing 91.77%, R-sq (adjusted) 87.20% and R-sq (predicted) 76.95% with insignificant lack of fit.

The main effect plot shows that the gas pressure and speed have maximum contribution on surface roughness; cutting speed and power have maximum contribution on kerf width and effect of block is very less on both responses may be due to less difference between the levels selected.

Minimum surface roughness can be obtained by operating at lower values of speed and gas pressure at any value of power, and minimum kerf width can be obtained by operating at minimum values of speed and gas pressure.

The Pie charts indicates that gas pressure and speed has contribution of 60.8% and 33.5% respectively on surface roughness and speed and power has contribution of 42.7% and 38.6% on kerf width. Other parameters contribute at minimum level.

The optimization results indicates that minimum surface roughness and kerf width of 2.63 µm and 0.1706 mm by operating at 1.1273 m/min speed, 1060.6061 w power and 12 bar gas pressure and the overall desirability of 0.9511 is obtained, it means that the confidence level is 95.11% indicated the model is fit.

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