Experimental Study of Fiber Laser Machining on C70600 material for kerf width and surface roughness

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Abstract

For many years laser machining process is widely used for dismantling jobs. But relatively only few research work have been addressed on the effect of high power fiber laser machining process on non ferrous materials. Most of the work is reported on ferrous materials like mild and stainless steel. In the nuclear sector there are significant quantities of non ferrous thick material like Copper (C 70600) that needs to be cut using laser process. In this paper, C 70600 is considered as workpiece material. Process parameters that are chosen are laser power, cutting speed and assist gas pressure. C 70600 material plate of thickness 8mm is selected. For experiments workpiece size of 30cm X 30cm is kept constant throughout. Performance parameters are kerf width and surface roughness. Fiber laser machining of 6kW output power machine is used for the experimental study. The kerf width and surface roughness are the important parameters that depend upon change in laser power and cutting speed. Kerf width and surface roughness increases with increase in laser power and cutting speed. Assist gas pressure did not show major effect on output parameters. Further, the experimental results have been optimized using Design Expert software implementing Box Behnken design method.

Key Words: *Laser assisted machining, Fiber laser, C70600, Design expert, Box Behnken design.*

1. INTRODUCTION

Laser is an acronym of Light Amplification by Stimulated Emission of Radiation. It is a source of light but it is different from other light sources. Laser makes a high intensity and extremely directional beam which has a narrow frequency range. These are more used as strong electromagnetic beam than a light beam. Lasers are used in optical disc, laser printers, barcode scanners, laser surgery and skin treatment, cutting and welding materials, military and low enforcement devices. It is a manufacturing process which can eliminate the need for machining or many engineering jobs, enabling you to save money on manufacturing cost. There are some types of lasers: CO2 Lasers, Neodymium (ND) Laser, Nd-YAG (Yttrium-Aluminum-Garnet) Laser, fiber laser. Laser cutting is a technology that uses laser to cut the material and it's typically used for industrial manufacturing applications. Laser cutting works by directing the output of a high-power laser most commonly through optics. The [laser optics] and CNC (computer numerical control) are used to direct the material or the laser beam generated. A commercial laser for cutting materials involved a motion control system to follow a CNC or G-code of the pattern to be cut onto the material. The focused laser beam is directed at the material, which then either melts, burns, vaporizes away, or is blown away by a jet of gas, leaving an edge with a high-quality surface finish. Industrial laser cutters are used to cut flat-sheet material as well as structural and piping materials. There are many different methods in cutting using lasers, with different types used to cut different material. Some of the methods are vaporization, melt and blow, melt blow and burn, thermal stress cracking, scribing, cold cutting and burning stabilized laser cutting. The Fibre laser process has been studied for dismantling work for more than 10 years. Among the cutting processes available, that using a multi-kilowatt laser is the process most commonly investigated. Fiber laser technology has many advantages compared to carbon dioxide laser technology. Specifically, the advent of high power (4+kW) lasers has provided a realistic opportunity for the use of lasers in decommissioning applications. The development of such lasers has further enhanced capability by providing scalable power in the multi-kilowatt regime with significantly better beam quality. Furthermore, power can be transmitted via several hundred meters of fiber optic cable, and hence the laser unit can be located some distance from the active area of operations. Also, low maintenance costs, high efficiency and small implantation space are advantages of this process . However, the main disadvantages of fiber compared with CO2 lasers relate to the efficiency when processing thicker materials, typically those above 5 mm. In fact, in the nuclear sector there are significant quantities of thick material that need to be effectively separated. The objective, in such types of work, is to minimize the kerf width in order to achieve minimum material loss and reduce the energy requirements. The physical processes involved in laser cutting of thick sections are complex. It is known that laser parameters, in particular laser power, focus settings, cutting speed, and assisting gas and its pressure, influence the physical processes in the cutting section. It was found that the higher the power intensity and the gas pressure are, the higher the thermal erosion in the kerf will be, but also the higher the thicknesses that can be cut. Furthermore, it is well known that to achieve cutting of larger thicknesses the laser power must increase and the cutting speed must decrease to maximize the heat input. However, recent studies on high power laser cutting have indicated that different focusing lenses do not affect the cutting characteristics. Fibre laser is a laser in which the active gain medium is an optical fibre doped with rare-earth elements such as erbium, ytterbium, neodymium, dysprosium, praseodymium, thulium and holmium.

2. LITERATURE REVIEW

R. Baumannb , P. Rauscher has publishes a paper on “Fast Laser Cutting of Thin Metal”. Since the emergence of high power single mode fiber lasers cutting velocity of 100m/min can be achieved easily on a straight cut. Results of laser fusion cutting of thin sheet metal with a 2kW single mode fiber and 4kW laser will be introduced. Several thicknesses of electrical sheets, aluminum sheets and high strength steel sheets have been cut with maximum speeds of 150m/min. The cutting quality in terms of cutting edge appearance, burr formation and kerf width has been analyzed.

A.M. Orishicha, A.G. Malikova, studied and published a paper on “Experimental comparison of laser cutting of steel with fiber and CO2 lasers on the basis of minimal roughness”. They compared the fiber and CO2 laser from the viewpoint two laser cutting methods, the oxygen – assisted cutting of low carbon steel and fusion cutting of stainless steel with a natural assistant gas. The absorbed laser energy was measured in respect to the unit of the removed material volume at the cutting parameters correlating to the minimal roughness of the cut surface.

S. Radonjić, P. Kovač and some other faculties of technical science publishes a paper on “Defining new processing parameters in laser cutting”. They states that Cutting parameters are scalar values which have a direct effect on the process of cutting. In order to properly modify the cutting parameters it is important to know how the part has been programmed and which cutting technology is used. The cutting of new material must be preceded by experimental cutting. If any problems concerning the quality of cutting should arise in the experimental phase, they can be fixed by adjusting the original cutting parameters.

A. Happonena, A. Stepanov , H. Piili , A. Salminen has published a paper on “Innovation Study for Laser Cutting of Complex Geometries with Paper Materials” states that even though technology for laser cutting of paper materials has existed for over 30 years, it seems that results of applications of this technology and possibilities of laser cutting systems are not easily available. The aim of this study was to analyze the feasibility of the complex geometry laser cutting of paper materials and to analyze the innovation challenges and potential of current laser cutting technologies offer.

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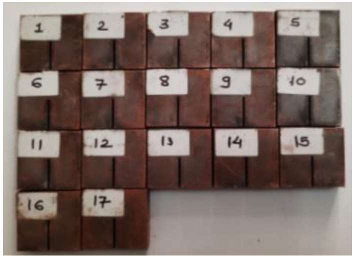
K.Huehnlein, K. Tschirpke, R. Hellmann, has published a paper on "Optimization of laser cutting processes using design of experiments". They stated briefly on an optimization study of laser cutting thin Al2O3 ceramic layers using a design of experiment approach (DOE). DOE allows to separate the most important influencing factors on the targeted cutting process, to clarify their interaction, to reduce the overall amount of parameter sets that need to be experimentally examined and to identify the optimized parameter regions, respectively.

3. DESIGN OF EXPERIMENT

The experiment was performed on a 6000W fibre laser system with CNC work table. The oxygen is used as an assist gas. The variable process parameters (or control parameters) taken are: Laser power, Cutting speed and Assist gas pressure. Laser wavelength is 1.08µm. Nozzle diameter (7mm), and nozzle gap (0.3mm) were kept constant throughout the experiment. The Copper sheet of thickness 8mm was taken as specimen. The quality characteristics analysed are surface roughness, kerf width, kerf taper angle, kerf deviation etc. The kerf width was measured using the Profile projector at 10x and 20x magnification. Surface roughness was measured on Surface roughness tester (Model SJ-210) with measuring speed: 0.25mm/s, 0.5mm/s, 0.75mm/s Returning: 1mm/s. The kerf deviation (K_d) in each experimental run is obtained by taking mathematical average of top kerf width and bottom kerf width. The kerf taper angle (K_t) was calculated using the following formula:

$$K_t(deg) = \frac{(K_{wt} - K_{wb}) \times 180}{2\pi t}$$

Where K_{wt} is top kerf width, K_{wb} is bottom kerf width and t is sheet thickness.



Copper plate (300×200mm)

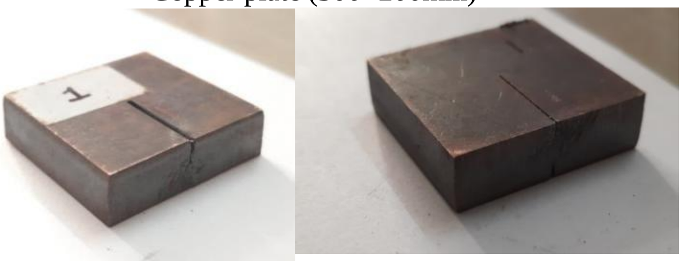


Table 1: Input parameters

	Sr.No	Name	Units	Low	High	-alpha	+alpha
	1	Laser power	watt	5500	6000	5500	6000
	2	Gas pressure	Bar	4	6	4	6
	3	Cutting speed	mm/min	400	600	400	600

Table 2: Results of surface roughness

		Factor 1	Factor 2	Factor 3	Response 1
Std	Run	A:Laser power	B:Gas pressure	C:Cutting speed	Surface Roughness
		watt	Bar	mm/min	Ra
12	1	5750	6	500	2.966
15	2	5750	5	500	2.735
4	3	6000	6	400	2.898
3	4	5500	6	400	3.621
9	5	5500	5	500	3.511
17	6	5750	5	500	2.999
7	7	5500	6	600	3.589
11	8	5750	4	500	2.878
6	9	6000	4	600	2.712
2	10	6000	4	400	2.753
8	11	6000	6	600	2.613
10	12	6000	5	500	2.849
1	13	5500	4	400	3.121
14	14	5750	5	600	2.942
16	15	5750	5	500	2.734
13	16	5750	5	400	2.832
5	17	5500	4	600	3.288

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ANOVA for Quadratic model

Response 1: Surface Roughness

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	1.52	9	0.1688	13.51	0.0012	significant
A-Laser power	1.09	1	1.09	87.40	< 0.0001	
B-Gas pressure	0.0874	1	0.0874	6.99	0.0332	
C-Cutting speed	0.0007	1	0.0007	0.0525	0.8253	
AB	0.0713	1	0.0713	5.70	0.0483	
AC	0.0266	1	0.0266	2.13	0.1882	
BC	0.0245	1	0.0245	1.96	0.2040	
A^2	0.1690	1	0.1690	13.52	0.0079	
B^2	0.0001	1	0.0001	0.0101	0.9227	
C^2	0.0047	1	0.0047	0.3757	0.5593	
Residual	0.0875	7	0.0125			
Lack of Fit	0.0408	5	0.0082	0.3503	0.8511	not significant
Pure Error	0.0466	2	0.0233			
Cor Total	1.61	16				

Factor coding is **coded**.
Sum of squares is **Type III - Partial**

The **Model F-value** of 13.51 implies the model is significant. There is only a 0.12% chance that an F-value this large could occur due to noise. **P-values** less than 0.0500 indicate model terms are significant. In this case A, B, AB, A^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The **Lack of Fit F-value** of
0.35 implies the Lack of Fit is not significant relative to the pure error. There is a 85.11% chance that a Lack of Fit F-value this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit.

Fit Statistics

Std. Dev.	0.1118		R^2	0.9455
Mean	3.00		Adjusted R^2	0.8755
C.V. %	3.72		Predicted R^2	0.8126
			Adeq Precision	11.3910

The **Predicted R^2** of 0.8126 is in reasonable agreement with the **Adjusted R^2** of 0.8755; i.e. the difference is less than 0.2. **Adeq Precision** measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 11.391 indicates an adequate signal. This model can be used to navigate the design space.

Final Equation in Terms of Coded Factors: Surface roughness =2.88335 + -0.3305 * A + 0.0935 * B + -0.0081 * C + - 0.094375 * AB + -0.057625 * AC + -0.055375 * BC + 0.251134 * A^2 + -0.0068662 * B^2 + -0.0418662 * C^2

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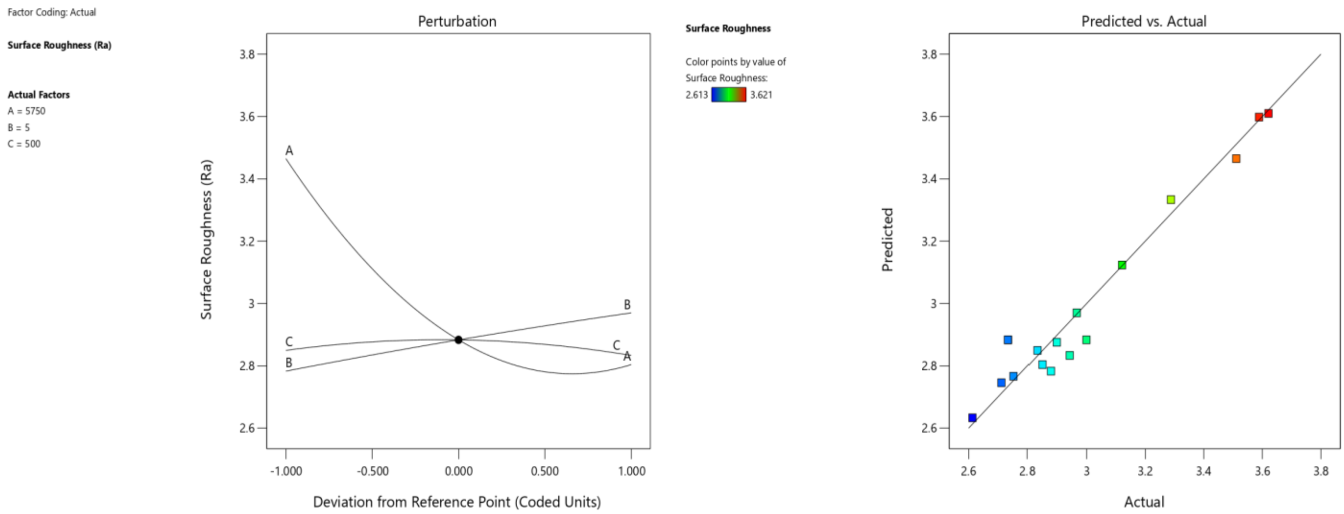
Final Equation in Terms of Actual Factors: Actual surface roughness =122.825 + -0.0444906 * Laser power + 2.60966 * Gas pressure + 0.0201281 * Cutting speed + -0.0003775 * Laser power * Gas pressure + -2.305e-06 * Laser power * Cutting speed + -0.00055375 * Gas pressure * Cutting speed + 4.01814e-06 * Laser power^2 + -0.0068662 * Gas pressure^2 + -4.18662e-06 * Cutting speed^2



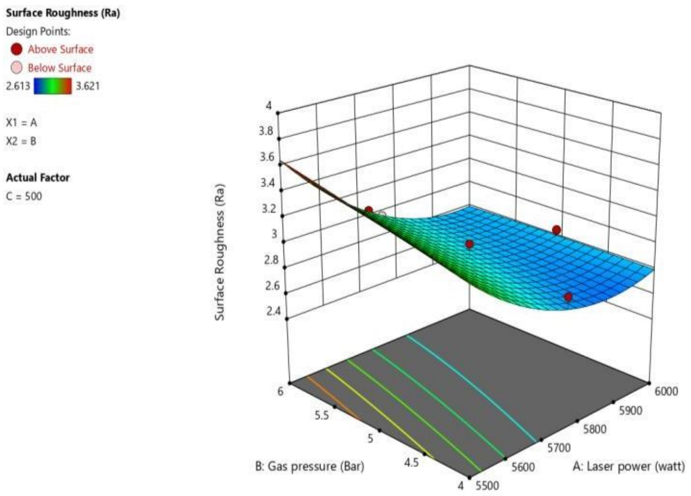


Table 3: Results for kerf width

		Factor 1	Factor 2	Factor 3	Response 2
Std	Run	A:Laser power	B:Gas pressure	C:Cutting speed	Kerf Width
		watt	Bar	mm/min	Mm
12	1	5750	6	500	0.25
15	2	5750	5	500	0.26
4	3	6000	6	400	0.24
3	4	5500	6	400	0.2
9	5	5500	5	500	0.27

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17	6	5750	5	500	0.25
7	7	5500	6	600	0.26
11	8	5750	4	500	0.29
6	9	6000	4	600	0.25
2	10	6000	4	400	0.26
8	11	6000	6	600	0.28
10	12	6000	5	500	0.26
1	13	5500	4	400	0.29
14	14	5750	5	600	0.25
16	15	5750	5	500	0.28
13	16	5750	5	400	0.21
5	17	5500	4	600	0.27

ANOVA for Quadratic model

Response 2: Kerf Width

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0085	9	0.0009	6.13	0.0130	significant
A-Laser power	0.0000	1	0.0000	0.0000	1.0000	
B-Gas pressure	0.0017	1	0.0017	11.00	0.0128	
C-Cutting speed	0.0012	1	0.0012	7.88	0.0263	
AB	0.0015	1	0.0015	9.85	0.0164	
AC	0.0000	1	0.0000	0.0814	0.7837	
BC	0.0021	1	0.0021	13.75	0.0076	
A^2	0.0002	1	0.0002	1.33	0.2866	
B^2	0.0005	1	0.0005	3.29	0.1126	
C^2	0.0018	1	0.0018	12.04	0.0104	
Residual	0.0011	7	0.0002			
Lack of Fit	0.0006	5	0.0001	0.5216	0.7590	not significant
Pure Error	0.0005	2	0.0002			
Cor Total	0.0096	16				

Factor coding is **coded**.
Sum of squares is **Type III - Partial**

The **Model F-value** of 6.13 implies the model is significant. There is only a 1.30% chance that an F-value this large could occur due to noise. **P-values** less than 0.0500 indicate model terms are significant. In this case B, C, AB, BC, C^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The **Lack of Fit F-value** of 0.52 implies the Lack of Fit is not significant relative to the pure error. There is a 75.90% chance that a Lack of Fit F-value this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit.

Fit Statistics

Std. Dev.	**0.0124**	R^2	**0.8875**
Mean	0.2571	Adjusted R^2	0.7427
C.V. %	4.82	Predicted R^2	0.2730
		Adeq Precision	9.0476

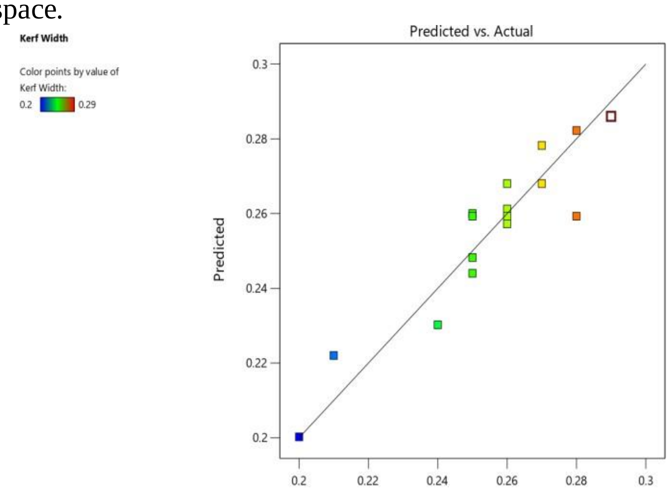
The **Predicted R^2** of 0.2730 is not as close to the **Adjusted R^2** of 0.7427 as one might normally expect; i.e. the difference is more than 0.2. This may indicate a large block effect or a possible problem with your model and/or data. Things to consider are model reduction, response transformation, outliers, etc. All empirical models should be tested by doing confirmation runs. **Adeq Precision** measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 9.048 indicates an adequate signal. This model can be used to navigate the design space.

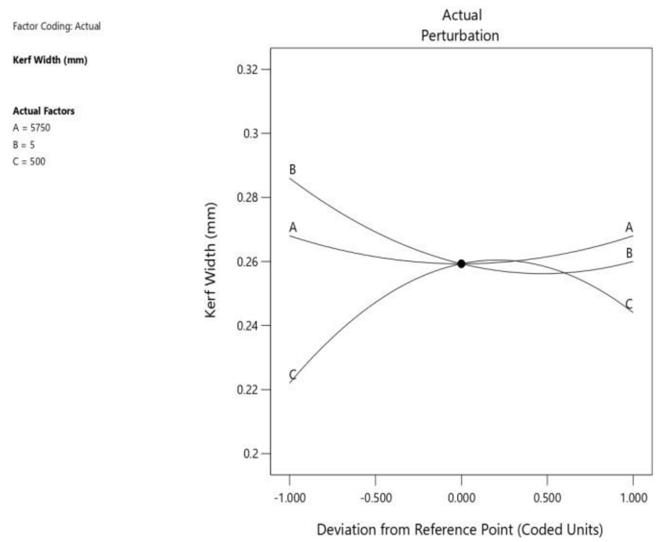
Final Equation in Terms of Coded Factors: Kerf width=0.2593*A+0.0000A-0.0130B+0.0110+0.0137AB- 0.0012AC+0.0163BC+0.0087A2+0.0137B2-0.0263C2

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients.

Final Equation in Terms of Actual Factors: Kerf width=+6.41910-0.001857 Laser power -0.547824 Gas pressure +0.002212 cutting speed +0.000055 laser power *gas pressure -5.00000E-08 laser power*cutting speed +0.000162 gas pressure * cutting speed + 1.39718E-07 laser power2 +0.013732 gas pressure2 -2.62676E-06 cutting speed2

The equation in terms of actual factors can be used to make predictions about the response for given levels of each factor. Here, the levels should be specified in the original units for each factor. This equation should not be used to determine the relative impact of each factor because the coefficients are scaled to accommodate the units of each factor and the intercept is not at the center of the design space.





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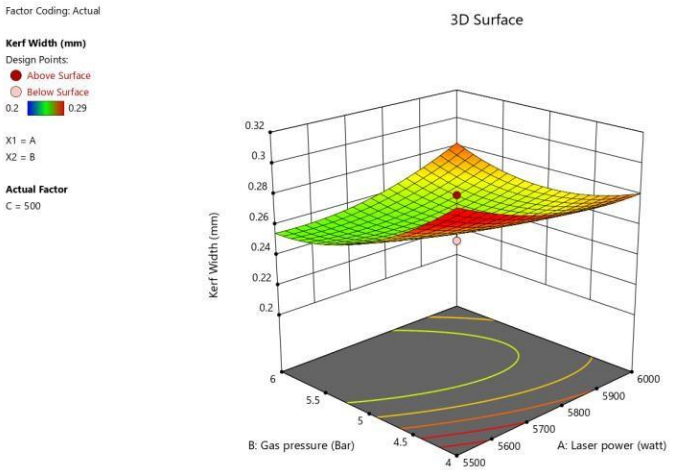

Table: Results for taper angle

		Factor 1	Factor 2	Factor 3	Response 3
Std	Run	A:Laser power	B:Gas pressure	C:Cutting speed	kerf taper angle
		watt	Bar	mm/min	Degree
12	1	5750	6	500	0.144566
15	2	5750	5	500	0.144567
4	3	6000	6	400	0.127433
3	4	5500	6	400	0.131622
9	5	5500	5	500	0.137435
17	6	5750	5	500	0.145433
7	7	5500	6	600	0.141622
11	8	5750	4	500	0.147429
6	9	6000	4	600	0.123244
2	10	6000	4	400	0.127433
8	11	6000	6	600	0.127433
10	12	6000	5	500	0.127433
1	13	5500	4	400	0.137433
14	14	5750	5	600	0.143244
16	15	5750	5	500	0.144563
13	16	5750	5	400	0.141622
5	17	5500	4	600	0.139055

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ANOVA for Quadratic model

Response 3: kerf taper angle

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	0.0010	9	0.0001	109.76	< 0.0001	significant
A-Laser power	0.0003	1	0.0003	285.93	< 0.0001	
B-Gas pressure	3.679E-07	1	3.679E-07	0.3582	0.5684	
C-Cutting speed	8.199E-06	1	8.199E-06	7.98	0.0256	
AB	6.906E-06	1	6.906E-06	6.72	0.0358	
AC	0.0000	1	0.0000	30.43	0.0009	
BC	0.0000	1	0.0000	19.22	0.0032	
A^2	0.0004	1	0.0004	383.40	< 0.0001	
B^2	5.559E-06	1	5.559E-06	5.41	0.0529	
C^2	0.0000	1	0.0000	11.77	0.0110	
Residual	7.189E-06	7	1.027E-06			
Lack of Fit	6.687E-06	5	1.337E-06	5.33	0.1656	not significant
Pure Error	5.023E-07	2	2.511E-07			
Cor Total	0.0010	16				

Factor coding is **coded**.
Sum of squares is **Type III - Partial**

The **Model F-value** of 109.76 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. **P-values** less than 0.0500 indicate model terms are significant. In this case A, C, AB, AC, BC, A^2, C^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model. The **Lack of Fit F- value** of 5.33 implies the Lack of Fit is not significant relative to the pure error. There is a 16.56% chance that a Lack of Fit F- value this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit.

Fit Statistics

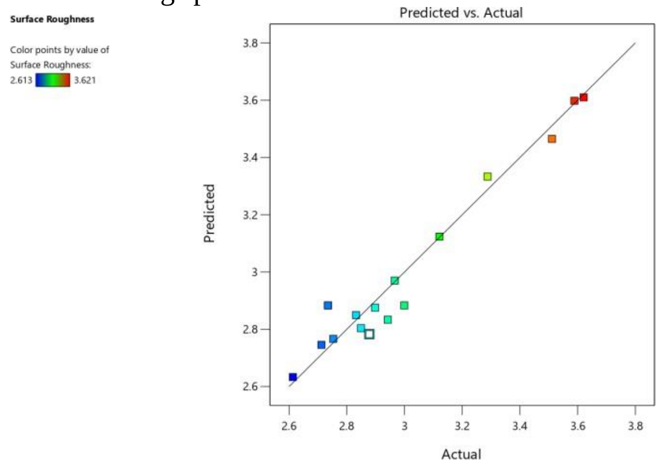
Std. Dev.	0.0010		R^2	0.9930
Mean	0.1372		Adjusted R^2	0.9839
C.V. %	0.7389		Predicted R^2	0.9133
			Adeq Precision	29.8962

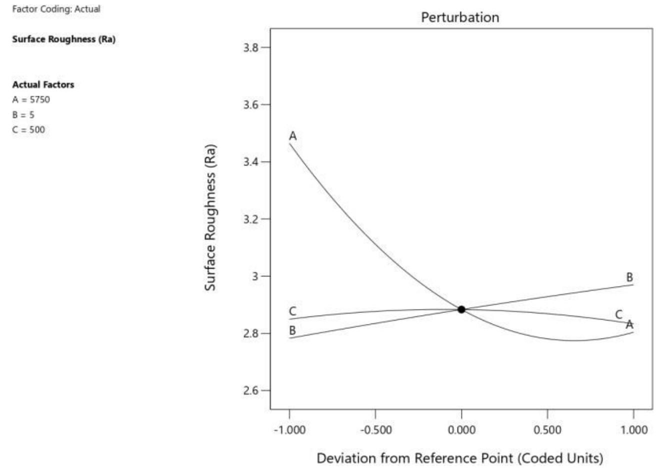
The **Predicted R^2** of 0.9133 is in reasonable agreement with the **Adjusted R^2** of 0.9839; i.e. the difference is less than 0.2. **Adeq Precision** measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 29.896 indicates an adequate signal. This model can be used to navigate the design space.

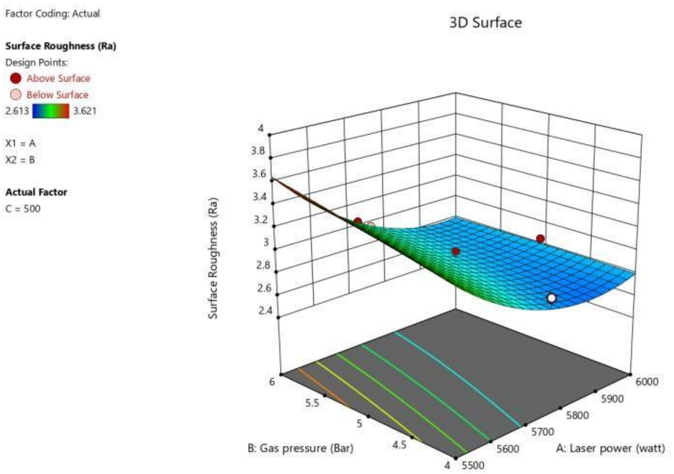
Final Equation in Terms of Coded Factors: Kerf taper angle=0.1447-0.0054 A -0.0002B +0.0009C +0.0009AB -0.0020 AC
+0.0016BC -0.0121A2 +0.0014B2 -0.0021C2

Final Equation in Terms of Actual Factors: Kerf taper angle= -6.24562 +0.002230Laser power-

0.043820Gas pressure
+0.000598 Cutting speed +3.71650E-06 Laser power * Gas pressure -7.90550E-08 Laser power * cutting speed -0.000016 Gas pressure * cutting speed -1.93970E-07 Laser power2 +0.001440 Gas pressure2 -2.12426E-07 Cutting speed2







4. OPTIMIZATION

Optimization is the action of maximizing or minimizing some function relative to some set, often representing a range of choices available in a certain situation. The function allows comparison of the different choices for determining which might be "best." We used Design Expert software for

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optimizing the parameters. In Design Expert the optimization module searches for a combination of factor levels that simultaneously satisfy the criteria placed on each of the responses and factors. To include a response in the optimization criteria it must have a model fit through analysis or supplied via an equation only simulation. Factors are automatically included “in range”. Numerical optimization uses the models to search the factor space for the best trade-offs to achieve multiple goals. Graphical optimization uses the models to show the volume where acceptable response outcomes can be found. Numerical Optimization chooses the desired goal for each factor and response from the menu. The possible goals are: maximize, minimize, target, within range, none (for responses only) and set to an exact value (factors only.) Graphical optimization displays the area of feasible response values in the factor space. Regions that do not fit the optimization criteria are shaded gray. Any “window” that is NOT gray shaded satisfies the goals for every response.

Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:Laser power	is in range	5500	6000	1	1	3
B:Gas pressure	is in range	4	6	1	1	3
C:Cutting speed	is in range	400	600	1	1	3
Surface Roughness	minimize	2.613	3.621	1	1	3
Kerf Width	minimize	0.2	0.29	1	1	3
kerf taper angle	minimize	0.123244	0.147429	1	1	3

From these constraints we found 75 solutions with different desirability from which the solution with higher desirability is selected.

Solutions:

Number	Laser power	Gas pressure	Cutting speed	Surface Roughness	Kerf Width	kerf taper angle	Desirability	
1	**6000.000**	**5.392**	**400.000**	**2.848**	**0.228**	**0.126**	**0.776**	**Selected**
2	6000.000	5.378	400.000	2.847	0.228	0.126	0.776	
3	5999.999	5.358	400.000	2.846	0.228	0.126	0.776	
4	5999.997	5.347	400.000	2.846	0.228	0.126	0.776	
5	5999.999	5.407	400.040	2.849	0.228	0.126	0.776	
6	6000.000	5.437	400.000	2.850	0.228	0.126	0.776	
7	5999.521	5.371	400.000	2.847	0.228	0.126	0.776	
8	6000.000	5.309	400.000	2.844	0.229	0.126	0.776	
9	5999.999	5.472	400.000	2.852	0.228	0.126	0.776	
10	5999.999	5.300	400.000	2.844	0.229	0.126	0.776	
11	5999.996	5.520	400.000	2.854	0.228	0.126	0.775	
12	6000.000	5.542	400.000	2.855	0.228	0.126	0.775	
13	5999.999	5.261	400.228	2.842	0.229	0.126	0.774	
14	6000.000	5.224	400.000	2.840	0.229	0.126	0.774	
15	5999.999	5.568	400.000	2.857	0.228	0.126	0.774	
16	5999.999	5.190	400.000	2.838	0.230	0.126	0.773	
17	5999.999	5.402	400.966	2.849	0.229	0.126	0.773	
18	6000.000	5.603	400.000	2.858	0.228	0.126	0.773	
19	6000.000	5.424	400.996	2.850	0.229	0.126	0.773	

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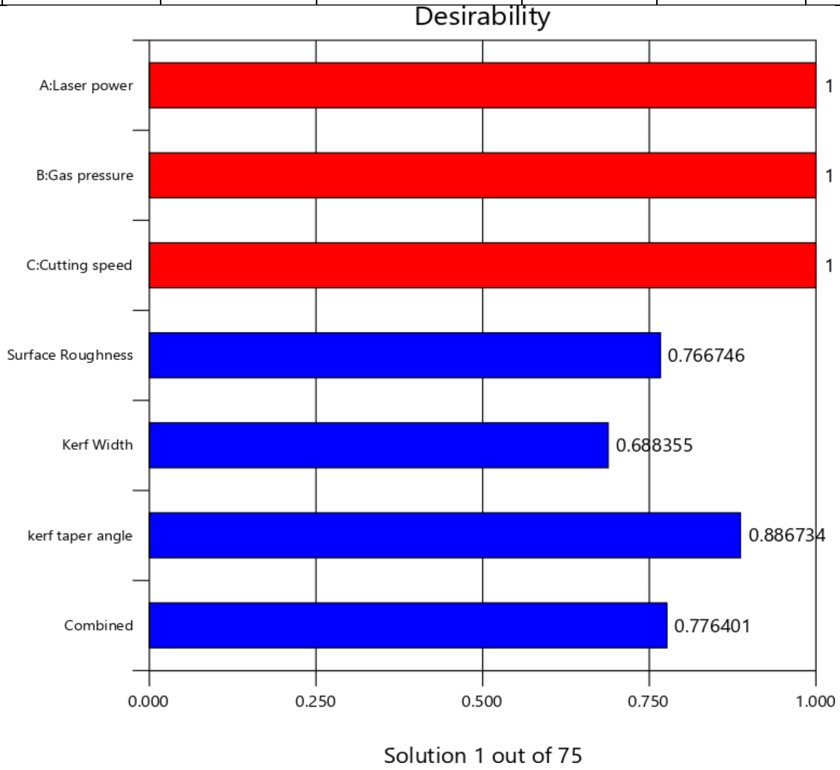
20	6000.000	5.177	400.000	2.837	0.230	0.126	0.773	
76	5599.174	5.307	400.000	3.168	0.214	0.139	0.514	
77	5601.349	4.795	600.000	3.133	0.249	0.143	0.329	



4. CONCLUSION

In this paper, a detailed study about Laser and Laser cutting process is done. Copper plate of thickness 8mm is considered which has been cut by fibre laser on Amada LCG 3015 AJ Fibre laser machine and for which various parameters were varied. After the actual cutting performed the readings taken were added into the DOE software from which graphs were obtained. At the last optimization is done from which optimized standard cutting parameters are achieved. In this experiment the effect of Laser power and cutting speed were more pronounced than the effect of assist gas pressure on surface roughness. The optimized parameters are Laser power: 6000W, Gas pressure: 5.391bar, cutting speed: 400 mm/min from which we get the Surface roughness (Ra):2.848, Kerf width: 0.228, kerf taper angle: 0.126 with desirability of 0.776.

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