Investigating the CO_2 laser cutting parameters of MDF wood composite material

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ABSTRACT

Laser cutting of medium density fibreboard (MDF) is a complicated process and the selection of the process parameters combinations is essential to get the highest quality of the cut section. This paper presents laser cutting of MDF based on design of experiments (DOE). CO_2 laser was used to cut three thicknesses 4, 6 and 9 mm of MDF panels. The process factors investigated are: laser power, cutting speed, air pressure and focal point position. In this work, cutting quality was evaluated by measuring, upper kerf width, lower kerf width, ratio between the upper kerf width to the lower kerf width, cut section roughness and the operating cost. The effect of each factor on the quality measures was determined and special graphs were drawn for this purpose. The optimal cutting combinations were presented in favours of high quality process output and in favours of low cutting cost.

Keywords: CO_2 laser cutting, design of experiment, MDF, optimization

1 Introduction

MDF is an engineered product characterized with great structural integrity, higher dimensional stability and greater flexibility in terms of shaping. Mass-production of this wood composite product commenced in the 1980s. MDF panels are suitable for many interior construction and industrial applications. The degree of surface roughness of the MDF panel plays an important role since any surface irregularities may show through thin overlays would reduce the final quality of the panel. The surface roughness depends on both raw characteristics and the fabricating processes procedures [1].

Currently, laser beam cutting is a fabrication process frequently used to cut parts of different materials such as MDF. In fact, cutting MDF boards by means of laser beam is a complicated process, as it involves an exothermic chemical reaction and it is influenced by several uncontrollable factors such as: composition, density, moisture, thermal conductivity and internal bond strength. Laser cutting of different materials has received more attention in the literatures, yet, few articles were published on the laser cutting of this wood composite product. Lum et al. [2] have reported the optimal cutting conditions for CO_2 laser cutting of MDF using full factorial technique. They found that, the average kerf width reduces with increasing the cutting speed. Also, they reported that no significant reduction in the kerf width has been found when varying the shielding gas pressure. Furthermore, they mentioned that increasing the gas pressure did not improve Ra values, however, the Ra values increases as the cutting speed increases. Finally, they pointed out that the maximum cutting speed for each thickness is independent to any increase in the gas pressure or type therefore it would be more economical to use compressed air than nitrogen to laser cut MDF. Lum et al. [3] have continued their investigation to estimate the variation in the power distribution with different cutting speed, material thickness and pulse ratios. Letellier and Ramos [4] have reported that when cutting MDF boards with thickness greater than 8 mm and keeping the focal position fixed at the surface this would result in curved side kerfs. This side curvature is more notorious as the MDF board thickness increases. Accordingly, they varied the focal position and beam velocity in order to investigate their effect on the shape of side kerfs. They suggested a focal position for each board thickness and process parameters. Also, they managed to determine the optimal cutting conditions by combining the plot of the focal position against board thickness for minimum side kerf with the plot of cutting velocity against board thickness at certain laser power. Barnekov et al. [5] have concluded that the factors affecting the ability of lasers to cut wood may be generally classified into three areas: characteristics of the laser beam, equipment and process variables and properties of the workpiece. They have reported that most lasers for cutting wood have powers ranged from 200 to 800 W. They have stated that, for a maximum efficiency, the proper combination of cutting speed and laser power will depend on workpiece thickness, density and the desired kerf width. Also, they have found that more power is required to cut wet wood than is required for dry wood if cutting speed is held constant. Barnekov et al. [6] have investigated laser cutting of wood composites, they have found that the optimal focus position is on the surface, using 400 to 500 W of laser power and cutting speed of 20 in/min. Moreover, they used compressed air with a nozzle diameter of 0.05 in. Finally, they reported that these preliminary results suggest that further research on laser cutting of wood to be done. N. Yusoff et al. [7] have studied CO_2 laser cutting of Malaysian light hardwood. They managed to outline the relationship between processing parameters and types of wood with different properties in terms of optimum cutting conditions. Also, they have presented guidelines for cutting a wide rage of Malaysian wood. The orientation of a linearly polarized beam has an effect on the kerf shape produced. When the beam is polarized in the cutting direction, the resulting cut may have a narrow kerf with sharp straight edges. On the other hand, if the beam is polarized at an angle to the cut direction, more absorption of the laser power takes place at the sides of the cut, producing a wider kerf with a taper that depends on the angle between the cutting direction and the plane of polarization [8 and 9]. Conducting an experiment using a systematic technique like DOE and artificial neural network (ANN) to investigate the behaviours of a certain manufacturing process with the aim of optimizing this process, such as optimizing laser welding or laser cutting processes, has been carried out by many researchers [10-11].

Hence, this work aims to investigate the effect of CO_2 laser cutting process parameters on the cut edge quality features (responses), and then to find out the optimal cutting conditions, which would lead to the desired quality features at a reasonable operating cost. Response surface methodology (RSM) technique has been implemented in order to find out the relationship between the process parameters and the responses.

2- Experimental Work

2.1 Design of experiment

Previously, the experiments used to be carried out by changing one-factor-at-a-time, this type of experimental approach required enormous number of runs to find out the effect of one factor, which is no longer followed as it is expensive and takes longer time. Another disadvantage is that the factors interaction can not be detected when using this approach. Therefore, other techniques, which overcome these obstacles, have to replace it, such as DOE, ANN etc [12-13]. A good literature review on the techniques used in optimizing certain manufacturing process and the selection of the appropriate technique has been outlined by Benyounis and Olabi [14]. For these reasons, a DOE approach has been selected to be implemented herein. In fact, there are many designs among DOE as mentioned in [14]. Two level factorial design and Taguchi method are the common designs, which have the less number of runs to study a process with multifactor and multi-responses such as laser cutting. However, the quadratic effect of each factor can not be determined using 2-level FD due to the limitation of this design as a screen design and some of the interactions between the factors affecting the process can not be determined using Taguchi method due to the aliased structures, which means not all the interaction effects can be estimated [15]. On the other hand, RSM is able to find out all the factor’s effects and their interactions. Eq1 below consists of three capital-sigma notations. The first summation term is representing the main factor effects, the second term is standing for the quadratic effects and the third term is representing the two factor interaction effects. Therefore, RSM was chosen by implementing Box-Behnken design, which is a three level design and it is able to investigate the process with a relatively small number of runs as compared with the central composite design [15, 16]. This design characterizes with its operative region and study region are the same, which would lead to investigate each factor over its whole range. In fact, this is a competitive advantage for this design over the central composite design [17].

$$y = b_o + \sum b_i \chi_i + \sum b_{ii} \chi_{ii}^2 + \sum b_{ij} \chi_i \chi_j + \varepsilon \tag{1}$$

RSM is a set of mathematical and statistical techniques that are useful for modelling and predicting the response of interest affected by several input variables with the aim of optimizing this response [15]. RSM also specifies the relationships among one or more measured responses and the essential controllable input factors [16]. If all independent variables are measurable and can be repeated with negligible error, the response surface can be expressed by:

$$y = f(x_1, x_2, \ldots x_k) \tag{2}$$

Where: k is the number of independent variables

To optimise the response “y”, it is necessary to find an appropriate approximation for the true functional relationship between the independent variables and the response surface. Usually a second order polynomial Eq.1 is used in RSM.

The values of the coefficients b_0, b_i, b_{ii} and b_{ij} can be calculated using regression analysis. The Prob.>F (sometimes called p-value) of the model and of each term in the model can be computed by means of analysis of variance (ANOVA). If the Prob.> F of the model and of each term in the model does not exceed the level of significance (say α= 0.05) then the model may be considered adequate within the confidence interval of (1- α). An adequate model means that the reduced model has successfully passed all the required statistical tests and can be used to predict the responses or to optimize the process etc.

In this study four process parameters are considered namely: laser power, cutting speed, air pressure and focal point position Table 1 shows process input parameters and experimental design levels used for the three thicknesses (4, 6 and 9 mm). The experimental data was analysed by statistical software, Design-Expert V7. Second order polynomials were fitted to the experimental data to obtain the regression equations. The sequential F-test, lack-of-fit test and other adequacy measures were carried out to select the best fit. A step-wise regression method was used to fit the second order polynomial Eq. 1 to the experimental data and to find the significant model terms [15, 16]. The same statistical software was used to generate the statistical and response plots as well as the optimization.

Table 1: Process variables and experimental design levels.

Parameter	Code	Unit	Levels								
			-1			0			+1		
			Thickness, mm			Thickness, mm			Thickness, mm		
			4	6	9	4	6	9	4	6	9
Laser power	A	kW	150	270	375	275	385	487.5	400	500	600
Cutting speed	B	mm/min	2000	2000	2000	3500	3500	3500	5000	5000	5000
Air pressure	C	bar	3	4	4	4.5	5.5	6	6	7	8
Focal point position	D	mm	-4	-6	-7	-2	-3	-3.5	0	0	0

2.2 Laser cutting

Dry panels of MDF wood composite in a sheet form was used as workpiece material. The sheet dimensions were 500 x 500 mm with thicknesses of 4, 6 and 9 mm. Trial laser cut runs were carried out by varying one of the process factors at-a-time to find out the range of each factor. Full cut, with an acceptable kerf width, cutting edge striations and dross were the criteria of selecting the working ranges for all factors. The main experiment was performed as per the design matrix in a random order to avoid any systematic error. A CW 1.5 kW CO_2 Rofin laser with a linear polarized beam angled at 45° provided by Mechtronic Industries Ltd. A focusing lens with a focal length of 127 mm was used to perform the cut. Fig. 1 shows the location of the focal plane relative to the upper surface for 6 mm MDF board. Among the trial laser cut runs, no significant difference has been noticed in terms of kerf width, roughness values and edge burn between the specimens processed using nitrogen and the ones processed using compressed air. As reported in [2] there is no significant reduction in the kerf width when using either the compressed air or nitrogen. In addition, the compressed air is cheaper than nitrogen. Therefore compressed air was supplied coaxially as an assist gas with different pressures. The nozzle used has a conical shape with nozzle diameter of 1.5 mm. Specimens were cut from the panel for each condition. The specimen shape was designed in order to allow the measurement of all responses in an accurate and simple way. The upper and lower kerf width 'responses' were measured using an optical microscope with digital micrometers attached to it with an accuracy of 0.001 mm, which allows measurement in both X-axis and Y-axis. An average of five measurements of both kerf widths was recorded for all runs. The ratio of the upper kerf to the lower kerf was calculated for each run using the averaged data. Five surface roughness values of each specimen were measured at the centre of the cut surface using a surface roughness tester model TR-200 and an average was calculated for each specimen. The design matrix and the average measured responses for each thickness are presented in Tables 2-4.

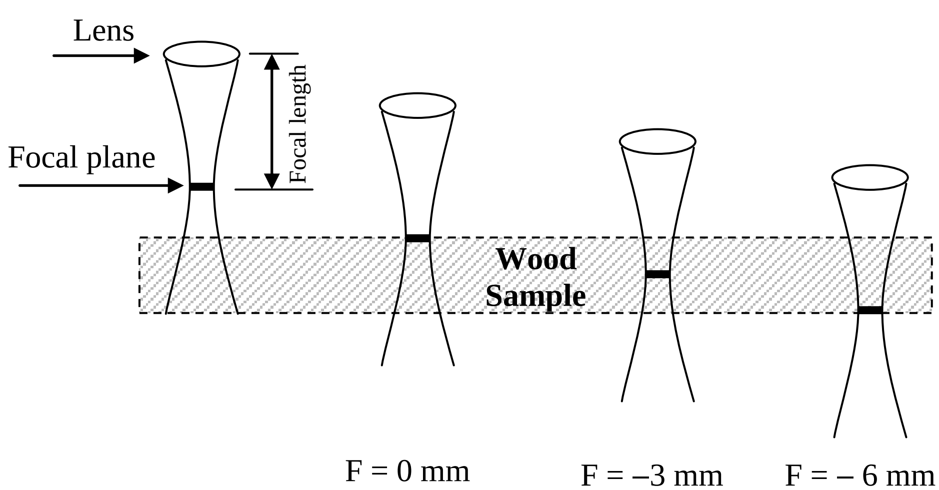


Fig. 1: Schematic plot showing the location of the focus of the beam relative to the upper surface.

Table 2: Design matrix and experimentally recorded responses for thickness 4 mm.

Std	Run	Factors				Responses				
		A: Laser power, W	B: Cutting speed, mm/min	C: Air pressure, bar	D : Focal position, mm	Upper kerf, mm	Lower kerf, mm	Ratio	Ra, µm	Cost €/m
1	25	150	2000	4.5	-2	0.326	0.232	1.404	5.857	0.0289
2	13	400	2000	4.5	-2	0.435	0.363	1.197	3.809	0.0322
3	1	150	5000	4.5	-2	0.267	0.134	1.997	6.877	0.0115
4	14	400	5000	4.5	-2	0.328	0.264	1.241	5.188	0.0129
5	24	275	3500	3	-4	0.694	0.246	2.822	5.785	0.0173
6	8	275	3500	6	-4	0.625	0.254	2.457	6.615	0.0176
7	22	275	3500	3	0	0.326	0.221	1.472	4.515	0.0173
8	23	275	3500	6	0	0.302	0.224	1.344	5.196	0.0176
9	17	150	3500	4.5	-4	0.633	0.132	4.800	6.860	0.0165
10	28	400	3500	4.5	-4	0.667	0.279	2.390	5.277	0.0184
11	27	150	3500	4.5	0	0.284	0.123	2.307	5.476	0.0165
12	3	400	3500	4.5	0	0.356	0.341	1.042	4.298	0.0184
13	29	275	2000	3	-2	0.450	0.324	1.388	4.248	0.0303
14	11	275	5000	3	-2	0.377	0.244	1.542	6.014	0.0121
15	16	275	2000	6	-2	0.420	0.335	1.253	5.827	0.0308
16	6	275	5000	6	-2	0.379	0.264	1.436	5.913	0.0123
17	12	150	3500	3	-2	0.369	0.128	2.875	5.083	0.0164
18	20	400	3500	3	-2	0.443	0.312	1.420	4.216	0.0183
19	5	150	3500	6	-2	0.333	0.138	2.423	6.145	0.0166
20	9	400	3500	6	-2	0.409	0.301	1.356	5.961	0.0185
21	26	275	2000	4.5	-4	0.680	0.301	2.261	5.663	0.0305
22	19	275	5000	4.5	-4	0.644	0.256	2.516	6.514	0.0122
23	4	275	2000	4.5	0	0.336	0.356	0.943	4.410	0.0305
24	18	275	5000	4.5	0	0.335	0.222	1.508	5.495	0.0122
25	15	275	3500	4.5	-2	0.400	0.245	1.631	5.253	0.0175
26	2	275	3500	4.5	-2	0.374	0.252	1.486	5.935	0.0175
27	21	275	3500	4.5	-2	0.417	0.240	1.741	6.339	0.0175
28	10	275	3500	4.5	-2	0.410	0.260	1.575	5.896	0.0175
29	7	275	3500	4.5	-2	0.340	0.255	1.335	6.368	0.0175

Table 3: Design matrix and experimentally recorded responses for thickness 6 mm.

Std	Run	Factors				Responses				
		A: Laser power, W	B: Cutting speed, mm/min	C: Air pressure, bar	D : Focal position, mm	Upper kerf, mm	Lower kerf, mm	Ratio	Ra, µm	Cost €/m
1	25	270	2000	5.5	-3.0	0.529	0.314	1.685	6.891	0.0306
2	28	500	2000	5.5	-3.0	0.588	0.410	1.435	5.488	0.0337
3	19	270	5000	5.5	-3.0	0.338	0.142	2.379	8.736	0.0123
4	24	500	5000	5.5	-3.0	0.401	0.278	1.441	6.961	0.0135
5	3	385	3500	4	-6.0	0.959	0.213	4.512	7.257	0.0183
6	14	385	3500	7	-6.0	0.910	0.235	3.867	8.684	0.0185
7	23	385	3500	4	0.0	0.327	0.196	1.670	6.567	0.0183
8	5	385	3500	7	0.0	0.326	0.193	1.684	7.186	0.0185
9	10	270	3500	5.5	-6.0	0.827	0.107	7.740	8.314	0.0175
10	9	500	3500	5.5	-6.0	0.983	0.279	3.519	6.906	0.0193
11	26	270	3500	5.5	0.0	0.304	0.179	1.703	7.353	0.0175
12	22	500	3500	5.5	0.0	0.375	0.221	1.697	5.332	0.0193
13	20	385	2000	4	-3.0	0.556	0.363	1.534	5.719	0.0320
14	15	385	5000	4	-3.0	0.433	0.234	1.851	7.325	0.0128
15	17	385	2000	7	-3.0	0.485	0.372	1.305	6.760	0.0324
16	11	385	5000	7	-3.0	0.533	0.248	2.148	8.071	0.0130
17	12	270	3500	4	-3.0	0.492	0.136	3.618	7.939	0.0174
18	1	500	3500	4	-3.0	0.545	0.297	1.838	5.721	0.0191
19	27	270	3500	7	-3.0	0.539	0.144	3.741	8.295	0.0176
20	21	500	3500	7	-3.0	0.577	0.302	1.909	6.480	0.0194
21	4	385	2000	5.5	-6.0	0.916	0.325	2.823	6.834	0.0322
22	13	385	5000	5.5	-6.0	0.840	0.205	4.096	8.757	0.0129
23	18	385	2000	5.5	0.0	0.365	0.381	0.957	5.193	0.0322
24	6	385	5000	5.5	0.0	0.336	0.202	1.661	7.524	0.0129
25	8	385	3500	5.5	-3.0	0.560	0.264	2.122	6.922	0.0184
26	16	385	3500	5.5	-3.0	0.448	0.253	1.772	7.072	0.0184
27	2	385	3500	5.5	-3.0	0.467	0.253	1.845	6.750	0.0184
28	7	385	3500	5.5	-3.0	0.569	0.255	2.228	6.620	0.0184
29	29	385	3500	5.5	-3.0	0.545	0.246	2.219	6.891	0.0184

Table 4: Design matrix and experimentally recorded responses for thickness 9 mm.

Std	Run	Factors				Responses				
		A: Laser power, W	B: Cutting speed, mm/min	C: Air pressure, bar	D : Focal position, mm	Upper kerf, mm	Lower kerf, mm	Ratio	Ra, µm	Cost €/m
1	15	375	2000	6	-3.5	0.580	0.338	1.717	8.221	0.0321
2	25	600	2000	6	-3.5	0.659	0.469	1.407	7.802	0.0352
3	7	375	5000	6	-3.5	0.475	0.180	2.646	9.690	0.0128
4	19	600	5000	6	-3.5	0.566	0.275	2.059	8.854	0.0141
5	13	487.5	3500	4	-7.0	0.935	0.192	4.860	9.459	0.0191
6	1	487.5	3500	8	-7.0	0.907	0.199	4.555	10.400	0.0194
7	18	487.5	3500	4	0.0	0.321	0.224	1.432	6.327	0.0191
8	5	487.5	3500	8	0.0	0.306	0.214	1.431	7.343	0.0194
9	28	375	3500	6	-7.0	0.883	0.132	6.679	10.411	0.0184
10	26	600	3500	6	-7.0	1.007	0.259	3.884	9.340	0.0201
11	10	375	3500	6	0.0	0.294	0.201	1.464	7.258	0.0184
12	20	600	3500	6	0.0	0.353	0.242	1.459	6.351	0.0201
13	12	487.5	2000	4	-3.5	0.650	0.432	1.505	7.377	0.0333
14	9	487.5	5000	4	-3.5	0.532	0.200	2.662	8.674	0.0133
15	17	487.5	2000	8	-3.5	0.662	0.410	1.616	8.749	0.0339
16	6	487.5	5000	8	-3.5	0.620	0.202	3.065	9.823	0.0136
17	3	375	3500	4	-3.5	0.646	0.178	3.633	7.521	0.0182
18	23	600	3500	4	-3.5	0.654	0.304	2.152	7.845	0.0199
19	22	375	3500	8	-3.5	0.621	0.176	3.531	9.125	0.0185
20	29	600	3500	8	-3.5	0.669	0.314	2.132	8.321	0.0203
21	4	487.5	2000	6	-7.0	0.950	0.362	2.626	9.185	0.0336
22	11	487.5	5000	6	-7.0	1.002	0.140	7.134	10.892	0.0135
23	2	487.5	2000	6	0.0	0.358	0.371	0.966	6.231	0.0336
24	21	487.5	5000	6	0.0	0.323	0.203	1.593	7.993	0.0135
25	16	487.5	3500	6	-3.5	0.602	0.200	3.006	8.382	0.0192
26	27	487.5	3500	6	-3.5	0.630	0.203	3.099	8.835	0.0192
27	14	487.5	3500	6	-3.5	0.594	0.196	3.036	8.072	0.0192
28	8	487.5	3500	6	-3.5	0.624	0.213	2.930	8.507	0.0192
29	24	487.5	3500	6	-3.5	0.642	0.217	2.964	9.099	0.0192

2.3 Estimating the laser cutting operating cost

Laser cutting operating costs can be estimated as cutting per hour or per unit length. The laser system used in this work utilized CO_2 using a static volume of laser gases of approximately 7.5 liter every 72 hour. For this laser system with 1.5 kW maximum out put power the operating costs generally falls into the categories listed in Table5. The operating cost calculation does not account the unscheduled break down and maintenance, such as break down in the table motion controller or PC hard disc replacement. The total approximated operating cost per hour as a function of process parameters can be estimated by 2.654+1.376xP +1.3718x10^{-5}xF. While the total approximated operating cost per unit length of the cut is given by Eq. 3 assuming 85% utilization. Eq. 3a was used to calculate the cutting cost per meter for all samples and the results were presented in Tables 2-4.

Table5: Operating costs break down.

Element of cost	Calculations	Cutting cost €/hr
Laser electrical power	(20.88 kVA)(0.8 pf)(€ 0.12359/kWhr)x(P/1.5)	1.376xP
Chiller electrical power	(11.52 kVA)(0.8 pf)(€ 0.12359/kWhr)	1.139
Motion controller power	(4.8 kVA)(0.8 pf)(€ 0.12359/kWhr)	0.475
Exhaust system power	(0.9 kWhr)(€ 0.12359/kWhr)	0.111
Laser gas LASPUR208	{(€1043.93/ bottle)/(1500liter/bottle)}x 7.5Liter/72hr	0.072
Gas bottle rental	(€181.37/720hr)	0.252
Chiller additives	(€284.80/year)/(8760 hr/year)	0.033
Compressed air	(0.111 kW/m^3)(€0.12359/kWhr)x(m^3/1000liter)	1.3718x10^{-5} [€/l] x F[l/hr]
Nozzle tip	(€7.20/200hr)	0.036
Exhaust system filters	(€5/100hr)	0.05
Focus lens	(€186/lens)/(1000hr)	0.186
Maintenance labor (with overhead)	(12 hr/2000hrs operation)(€50/hr)	0.30
Total operation cost per hour		2.654+1.376xP +1.3718x10^{-5}xF

$$\text{Cutting cost[Euro/m]} = \frac{2.654 + 1.376 \times \text{P[kW]} + 1.3718\text{x}10^{-5} \times \text{F[l/hr]}}{(0.85) \times \text{S[mm/min][60min/hr][m/1000mm]}} \tag{3}$$

$$\text{Cutting cost[Euro/m]} = \frac{2.654 + 1.376 \times \text{P} + 1.3718\text{x}10^{-5} \times \text{F}}{0.051 \times \text{S}} \tag{3a}$$

Where

P: used out put power in kW.

F: flow rate in l/hr.

S: cutting speed in mm/min.

At pressure above 0.89 bar the compressed air will flow in a supersonic manner. Note that this pressure value (0.89 bar) is independent of nozzle diameter. At pressure above this threshold the flow rate in [l/hr] of the compressed air through a nozzle can be easily calculated from Eq. 4 [18].

$$\text{Flow rate} = \text{F[l/hr]} = 492 \times d^2 \left(p_g + 1\right) \tag{4}$$

Where:

d: Nozzle diameter [mm].

P_g: Nozzle supply pressure [bar].

3. Results and Discussion

3.1 Analysis of Variance

In this research, fifteen ANOVA tables for the reduced quadratics models have been obtained, but to avoid any confusion for the reader these tables were abstracted to present only the most important information as shown in Table 6. This table shows also the other adequacy measures R^2, Adjusted R^2 and predicted R^2. The entire adequacy measures are close to 1, which is in reasonable agreement and indicate adequate models. The values of adequacy measures are in good form as compared with the values listed in [11 and 12]. There is one case were the lack-of-fit is significant at both level of significant 1% and 5%. This case is for the ratio model for 9 mm thick MDF, which has a significant lack-of-fit, this may result in inapplicability for this model in some point in the design space. The developed mathematical models are listed below in terms of coded factors. Eqs 5-9 are mathematical models for 4 mm thick MDF, Eqs 10-14 are mathematical models for 6 mm thick MDF and Eqs. 15-19 are mathematical models for 9 mm thick MDF. From these mathematical models one can notice the significant factors that would principally affect each response as they appear in the model.

Table 6: Abstracted ANOVA Tables for all reduced quadratic models.

Thickness, mm	Response	SS_{-model}	DF	Lack of Fit	Prob. >F Model	R^2	Adj- R^2	Pre- R^2
4	Upper kerf	0.45	6	Not Sig.	< 0.0001 (Sig.)	0.9648	0.9552	0.9398
	Lower kerf	0.12	7	Not Sig.	< 0.0001 (Sig.)	0.9619	0.9492	0.9492
	Ratio	15.28	7	Not Sig.	< 0.0001 (Sig.)	0.8828	0.8437	0.6318
	Ra	15.21	4	Not Sig.	< 0.0001 (Sig.)	0.7881	0.7528	0.7098
	Cost	0.001131	6	-	< 0.0001 (Sig.)	0.9999	0.9999	0.9997
6	Upper kerf	1.12	7	Not Sig.	< 0.0001 (Sig.)	0.9629	0.9505	0.9294
	Lower kerf	0.16	8	Not Sig.	< 0.0001 (Sig.)	0.9677	0.9548	0.9182
	Ratio	48.75	7	Not Sig.	< 0.0001 (Sig.)	0.9134	0.8845	0.7291
	Ra	25.45	4	Not Sig.	< 0.0001 (Sig.)	0.9324	0.9211	0.8999
	Cost	0.001251	6	-	< 0.0001 (Sig.)	0.9999	0.9999	0.9997
9	Upper kerf	1.18	3	Not Sig.	< 0.0001 (Sig.)	0.9686	0.9648	0.9537
	Lower kerf	0.21	10	Not Sig.	< 0.0001 (Sig.)	0.9849	0.9765	0.9547
	Ratio	1.23	7	Sig.*	< 0.0001 (Sig.)	0.9727	0.9636	0.9274
	Ra	38.12	4	Not Sig.	< 0.0001 (Sig.)	0.9437	0.9343	0.9201
	Cost	0.001365	6	-	< 0.0001 (Sig.)	0.9999	0.9999	0.9998

* Significant at both $\alpha = 0.001$ & 0.05.

$$\text{Upper kerf} = 0.39 + 0.036*A - 0.026*B - 0.016*C - 0.17*D - 0.023*A^2 + 0.11*D^2 \quad (5)$$

$$\text{Lower kerf} = 0.25 + 0.081*A - 0.044*B + 0.0017*D + 0.018*AD - 0.022*BD$$

$$-0.031*A^2 + 0.038*B^2 \quad (6)$$

$$Ratio = 1.59 - 0.60*A + 0.15*B - 0.72*D + 0.29*AD + 0.38*A^2 - 0.34*B^2 + 0.55*D^2 \quad (7)$$

$$Ra = 5.55 - 0.63*A + 0.52*B + 0.48*C - 0.61*D \quad (8)$$

$$Operating\ cost = 0.017 + 0.00036*A – 0.009164*B + 0.0001372*C – 0.0005059*AB - 0.000067*BC + 0.003928*B^2 \quad (9)$$

$$Upper\ kerf = 0.52 + 0.037*A - 0.047*B + 0.0048*C - 0.28*D + 0.043*BC - 0.032*B^2 + 0.11*D^2 \quad (10)$$

$$Lower\ kerf = 0.25 + 0.064*A - 0.071*B + 0.0007*D - 0.033*AD - 0.015*BD - 0.023*A^2 + 0.060*B^2 - 0.032*D^2 \quad (11)$$

$$Ratio = 2.14 - 0.75*A + 0.32*B - 1.43*D + 1.05*AD + 0.51*A^2 - 0.67*B^2 + 0.91*D^2 \quad (12)$$

$$Ra = 7.05 - 0.89*A + 0.87*B + 0.41*C - 0.63*D \quad (13)$$

$$Operating\ cost = 0.018 + 0.000953*A – 0.009654*B + 0.0001372*C – 0.0004654*AB - 0.00067*BC + 0.004138*B^2 \quad (14)$$

$$Upper\ kerf = 0\ 62 + 0.034*A - 0.028*B - 0.31*D \quad (15)$$

$$Lower\ kerf = 0.21 + 0.055*A - 0.098*B – 0.0013*C + 0.014*D - 0.022*AD + 0.013*BD + 0.021*A^2 + 0.086*B^2 + 0.019*C^2 - 0.019*D^2 \quad (16)$$

$$1/(Ratio) = 0.35 + 0.060*A - 0.14*B + 0.26*D - 0.042*BD + 0.032*A^2 + 0.14*B^2 + 0.077*D^2 \quad (17)$$

$$Ra = 8.49 - 0.31*A + 0.70*B + 0.55*C - 1.52*D \quad (18)$$

$$Operating\ cost = 0.019 + 0.0009323*A - 0.010*B + 0.0001829*C – 0.0004553*AB - 0.00008933*BC + 0.004325*B^2 \quad (19)$$

3.3 Validation of the Developed models

In order to verify the adequacy of the developed models, two confirmation experiments for each thickness were carried out using a new test conditions, these experiments are randomly selected from the optimization results, which are within the investigated range. Using the point prediction option in the software, all the responses values can be predicted by substituted these conditions into the previous developed models. Tables 7 presents the experiments condition, the actual experimental values, the predicted values and the percentages of error for all thicknesses. It is clear that all the values of the percentage of the error for all the four responses are within resalable agreement. Therefore, the models are valid. It is apparent from Table 7 that the ratio model for thickness 9 mm has the highest percentage of error of -17.397% in the second validation experiment, this is due to the fact that this model has a significant lack-of-fit, which may lead to the model would not fit and as a result of this the model might not perform adequately in some region in the design space. However, if we calculate the predicted ratio for this case by dividing the predicted upper kerf of 0.299 by the predicted lower kerf of 0.207 the percentage of error would equal to 5.125 %, which is in excellent agreement. In balance, the ratio model for 9 mm MDF may not be used in predicting, but still can be used to investigate the general influence of the process parameters on the ratio and in the optimization.

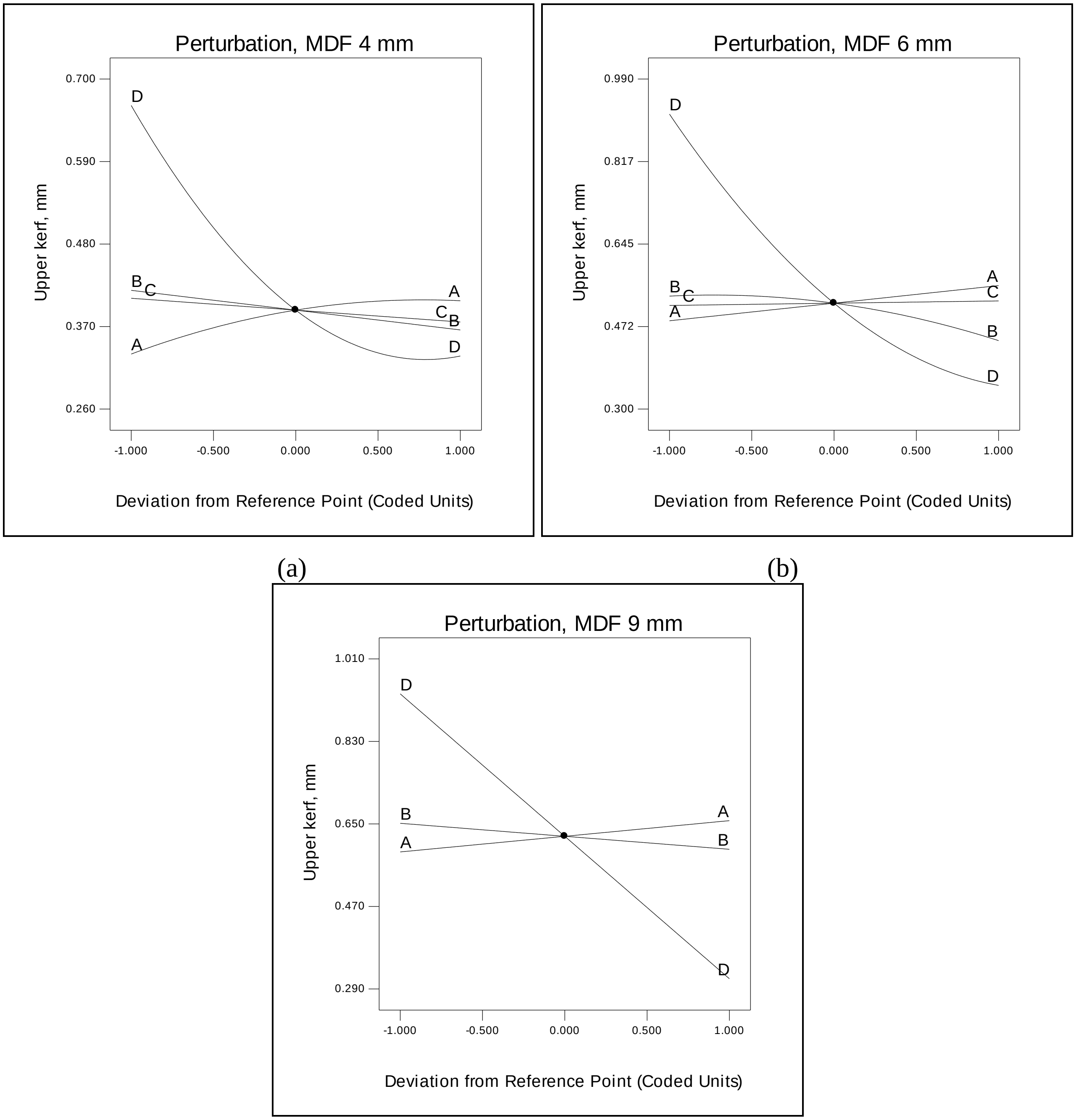
Table 7: Confirmation experiments.

Thick-ness, mm	Exp. No.	Factors				Values	Responses				
		A, W	B, mm/min	C, bar	D, mm		Upper kerf, mm	Lower kerf, mm	Ratio	Ra, µm	Cost, €/m
4	1	400	2164.51	4.08	-0.29	Actual	0.358	0.407	0.879	3.598	0.0297
						Predicted	0.367	0.4	1	3.809	0.0302
						Error %	-2.629	1.672	-13.758	-5.876	-1.684
	2	150	4999.99	3	-1.72	Actual	0.303	0.136	2.220	5.632	0.0115
						Predicted	0.302	0.124	2.241	6.129	0.0116
						Error %	0.264	9.091	-0.949	-8.832	-0.870
6	1	482.29	2000	6.41	-0.69	Actual	0.369	0.406	0.909	5.120	0.0336
						Predicted	0.392	0.388	1	5.193	0.0335
						Error %	-6.348	4.339	-10.038	-1.418	0.298
	2	270	5000	4	-3.54	Actual	0.441	0.137	3.210	7.629	0.0122
						Predicted	0.413	0.146	3.525	8.515	0.0123
						Error %	6.349	-6.259	-9.827	-11.614	-0.820
9	1	600	2000	4.14	-0.77	Actual	0.416	0.477	0.874	5.358	0.0349
						Predicted	0.444	0.456	1	5.791	0.0348
						Error %	-6.628	4.322	-14.457	-8.089	0.287
	2	375	5000	4	-0.55	Actual	0.322	0.212	1.522	6.788	0.0127
						Predicted	0.299	0.207	1.787	7.67	0.0129
						Error %	7.258	2.266	-17.397	-12.990	-1.575

3.5 Discussion

3.5.1 Upper kerf

The perturbation plots for the upper kerfs for all thicknesses are shown in Fig. 2. In this graph it is clear that the focal point position is the major factor affecting the upper kerf. The results show that the upper kerf decreases as the focal point position increases and this is in agreement with the logic as the smallest spot size of the laser beam occurs at the surface when the focal point is exactly on the surface and consequently the laser power will localize in narrow area. On the other hand, defocusing the beam below the surface would result in spreading the laser power onto wider area on the surface, which at the end leads to a wider upper kerf. The upper kerf is on average of 2.5 times wider when using defocused beam. From the same figure, it is notable that the laser power is also affecting the upper kerf. The upper kerf would increase as the laser power increases. Finally, it is clear that the upper kerf reduces slightly as the cutting speed and gas pressure increase these observations are in agreement with Lum et al. [3]. However, the effect of the gas pressure on the average upper kerf trims down as the thickness increases until it disappears for 9 mm thick MDF. Fig. 3 is interaction graph showing the interaction effect between the cutting speed and the air pressure on the average upper kerf for 6 mm MDF. It is demonstrated from Fig. 3 that at slower cutting speed less than 3337.58 mm/min a narrower upper kerf would be achieved by using higher air pressure of 7 bars. Alternatively, a narrower average upper kerf could be obtained by using faster cutting speed above 3337.58 mm/min and an air pressure of 4 bars.



(a) (b)

(c)

Fig. 2: Perturbation plots showing the effect of each factor on the average upper kerf for the (a) 4 mm thick, (b) 6 mm thick and (c) 9 mm thick.

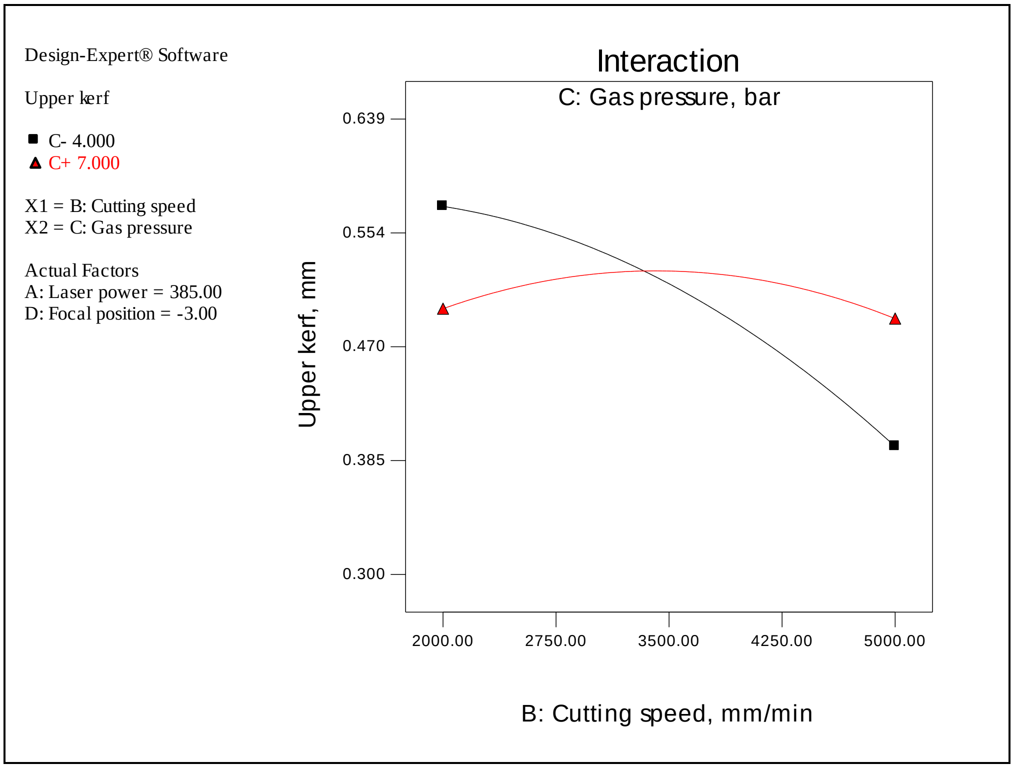
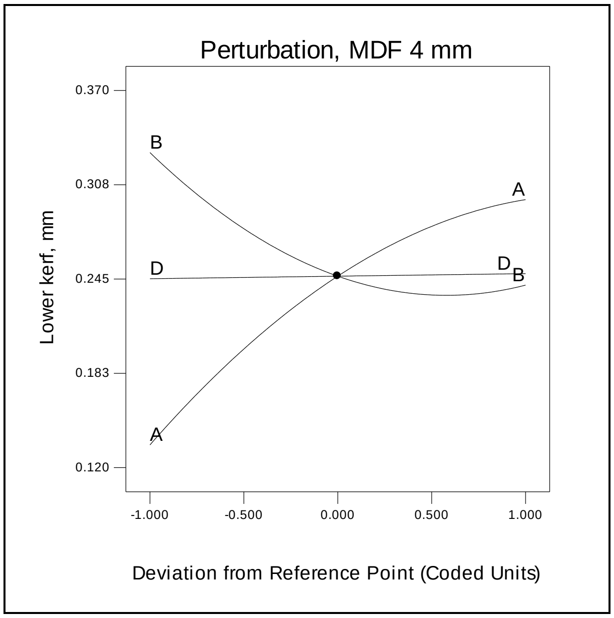


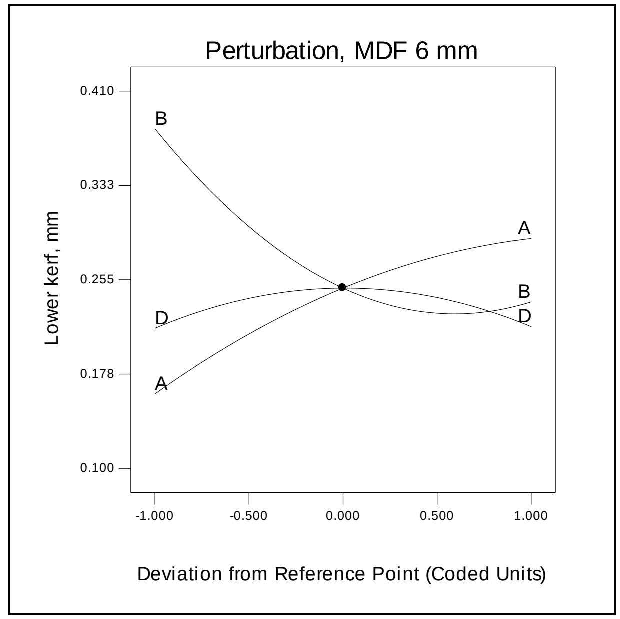
Fig. 3: Interaction graph between cutting speed and gas pressure for 6 mm MDF.

3.5.2 Lower kerf

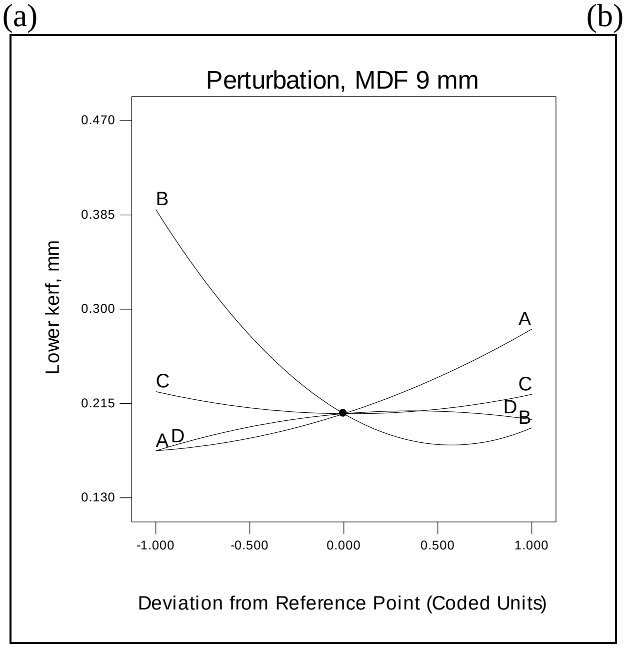
The perturbation plots for the average lower kerf widths for all thicknesses are exhibited in Fig. 4. In this plot it is obvious that the laser power and the cutting speed are the major factors, which have an effect on the lower kerf. The results confirmed that the lower kerf decreases as the cutting speed increases and this is in agreement with Lum et al [3]. Also, it was found that the lower kerf increases as the laser power increases and it is in good agreement with results found in the literatures. When using the highest laser power, the lower kerf is on average of 2.21 times wider than the one obtained when using the lowest laser power. By using the slowest cutting speed, the lower kerf is on average of 1.37 times wider than the one obtained when using the fastest cutting speed. It is evident that the lower kerf changes slightly as the focal point position increases. However, the air pressure has a very minor effect on the average lower kerf for 9 mm thick MDF only. Fig. 5(a-c) is interaction graph showing the interaction effect between the cutting speed and the focal point position on the average lower kerf for the three thicknesses. It is demonstrated from Fig. 5(a-b) that at slower cutting speed less than 3337.58 mm/min or 3570.03 mm/min for 4 or 6 mm thick respectively a narrower lower kerf would be achieved by using focal point position of -4 mm or -6 mm. On the other hand, a narrower average lower kerf could be obtained by using faster cutting speed above 3337.58 mm/min or 3570.03 mm/min for the same two thicknesses and a focused beam. Form Fig. 5(c), it is clear that at slowest cutting speed both focal point positions would lead to the same lower kerf, but as the speed increases a focal position of -7 mm would lead to a narrower lower kerf. It is evident from Fig. 5(a-c) that the effect of the focal point position becomes insignificant when using slow cutting speed.



(a)

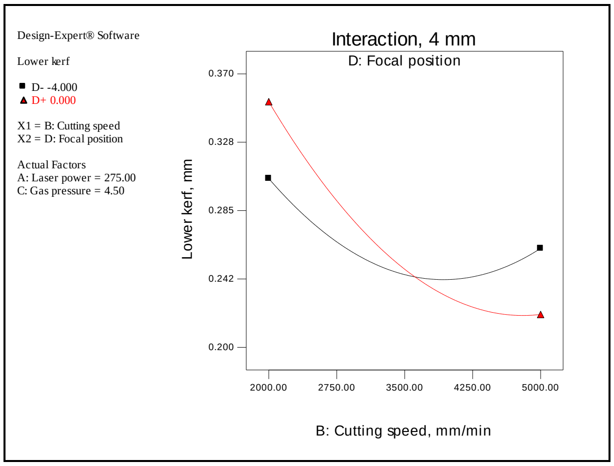


(b)

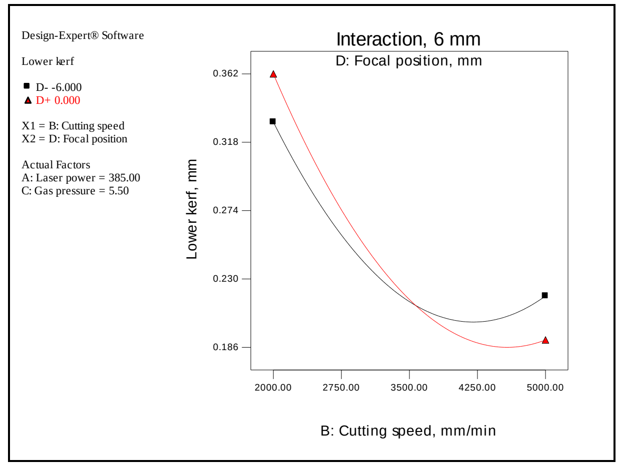


(c)

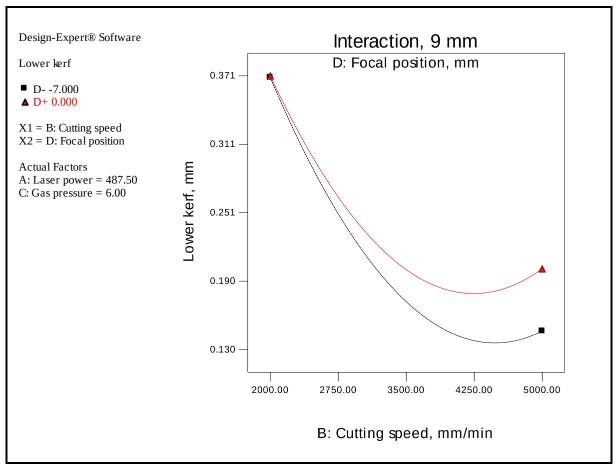
Fig. 4: Perturbation plots showing the effect of each factor on the average lower kerf for the (a) 4 mm thick, (b) 6 mm thick and (c) 9 mm thick.



(a)



(b)

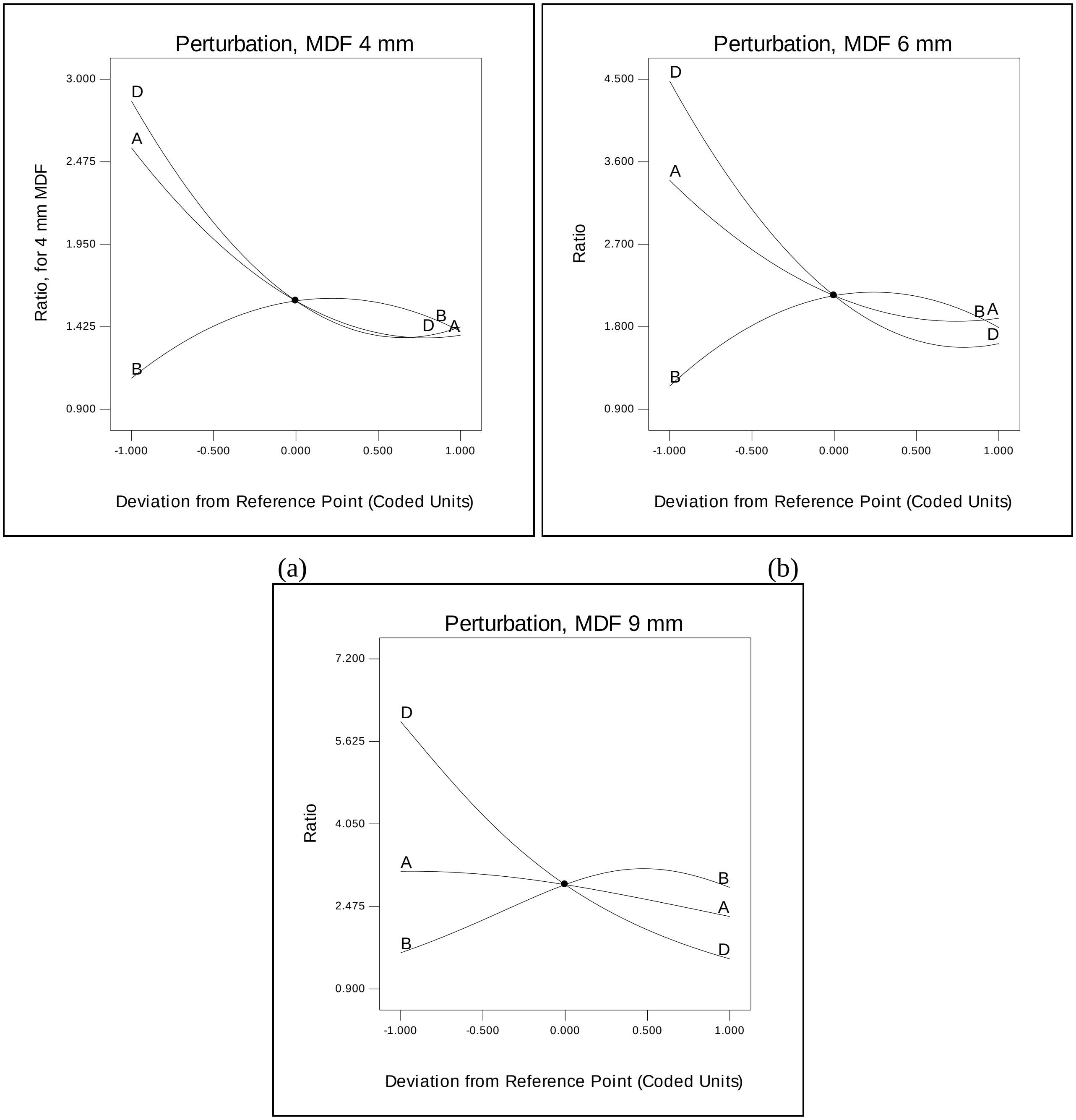


(c)

Fig. 5: Interaction graph between cutting speed and focal point position for the three thicknesses.

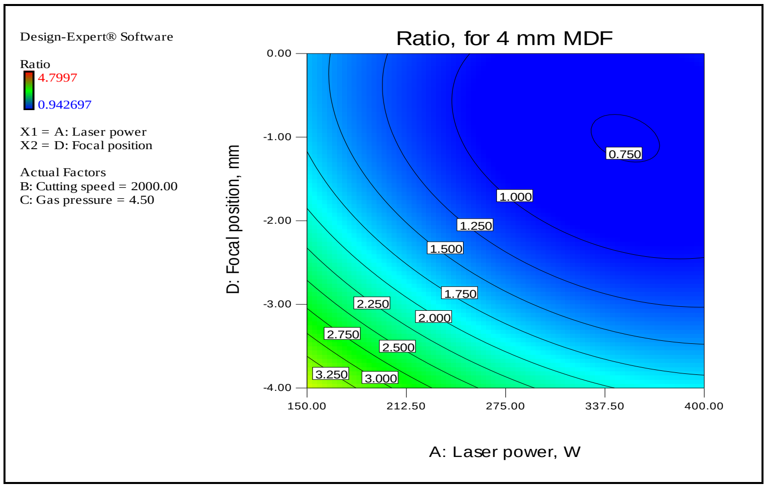
3.5.3 Ratio between upper kerf to lower kerf

The perturbation plots for the ratio between the upper kerf to the lower kerf for all thicknesses are presented in Fig. 6(a-c). In this plot it is obvious that the focal position has the main role on the ratio between the upper kerf to the lower kerf. The results show that the ratio decreases as the focal position increases. It can be seen from Fig. 6(a-c) that the laser power has the second main effect on the ratio. However, this effect reduces as the thickness increases. In general, the ratio decreases as the laser power increases. Also, it was found that the ratio increases as the cutting speed increases up to around 3875 mm/min, and then it starts to decrease as the cutting speed increases However, the air pressure has no effect on the ratio for all thicknesses. Fig. 7(a-c) is contours graph showing the effect of the focal point position and the laser power on the ratio for the three thicknesses. It is apparent from Fig. 7(a-b) the area where the ratio between the upper kerf to the lower kerf is around 1, which is the desirable ratio in order to obtain square cut edge.

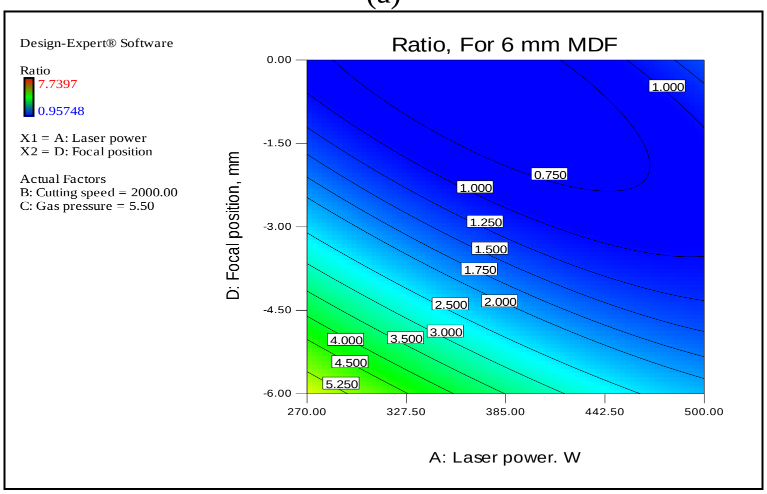


(a) (b) (c)

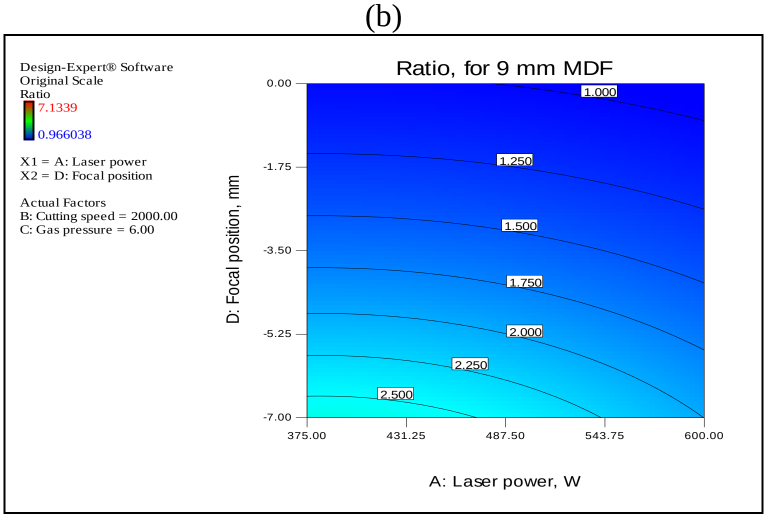
Fig. 6: Perturbation plots showing the effect of each factor on the ratio for the (a) 4 mm thick, (b) 6 mm thick and (c) 9 mm thick.



(a)



(b)

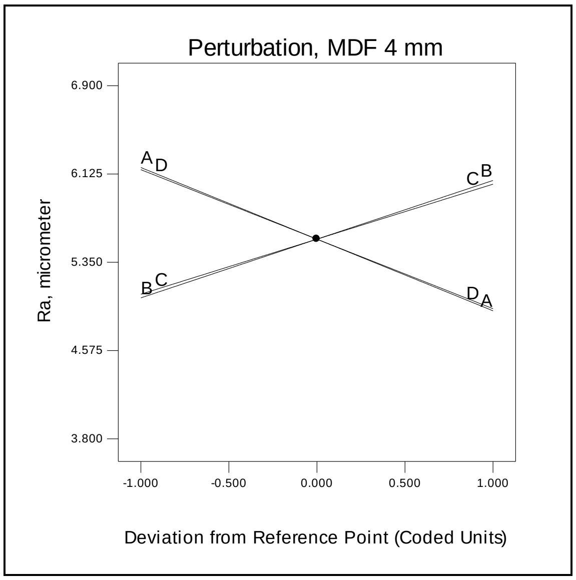


(c)

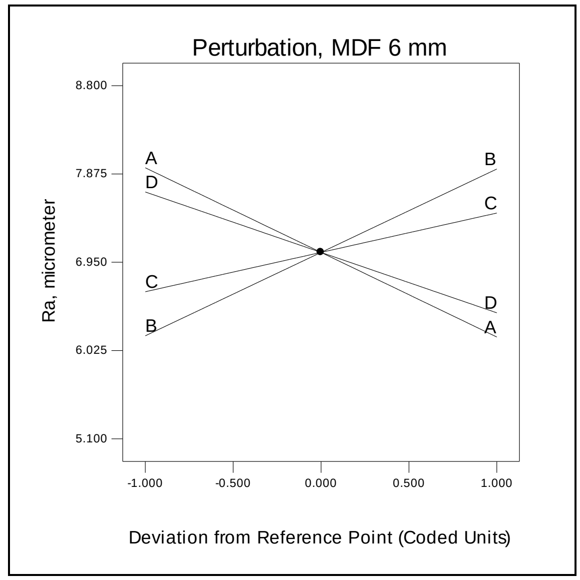
Fig. 7: Contours graph showing the effect of focal point position and laser power for the three thicknesses.

3.5.4 Roughness

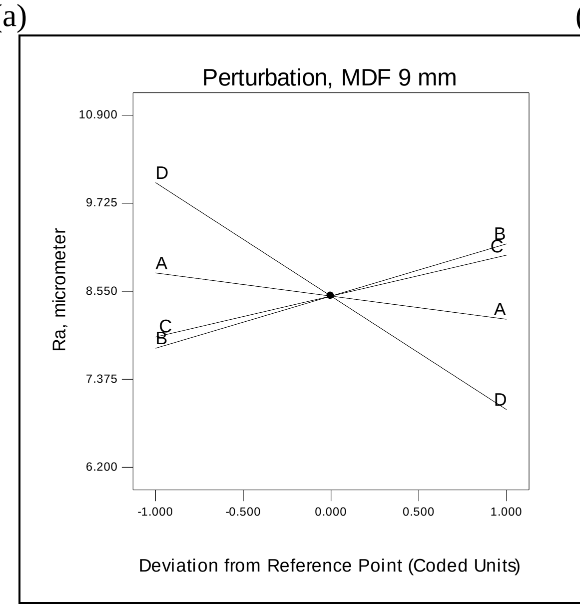
The perturbation graphs for the roughness for all thicknesses are shown in Fig. 8(a-c). In this graph it is clear that all the factors are affecting the roughness significantly. The results show that the roughness decreases as the focal point position and laser power increase and this is in agreement with the results reported by Barnekov et al. [6]. However, the effect of laser power on the roughness of the cut surface reduces as a thicker MDF sheet is considered to be cut. The results demonstrated that the roughness value increases as the cutting speed and gas pressure increase.



(a)



(b)

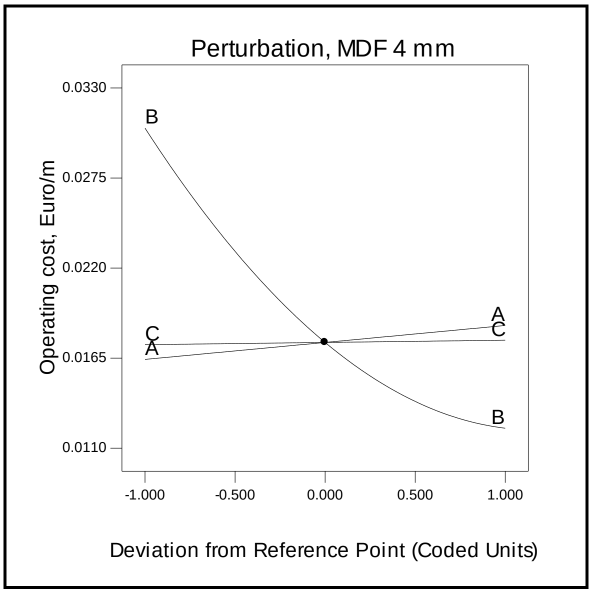


(c)

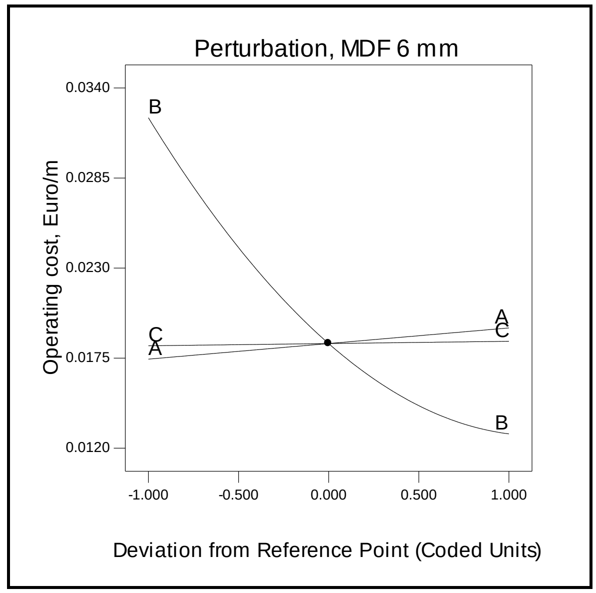
Fig. 8: Perturbation plots showing the effect of each factor on the roughness for (a) 4 mm thick, (b) 6 mm thick and (c) 9 mm thick MDF.

3.5.5 Operating cost

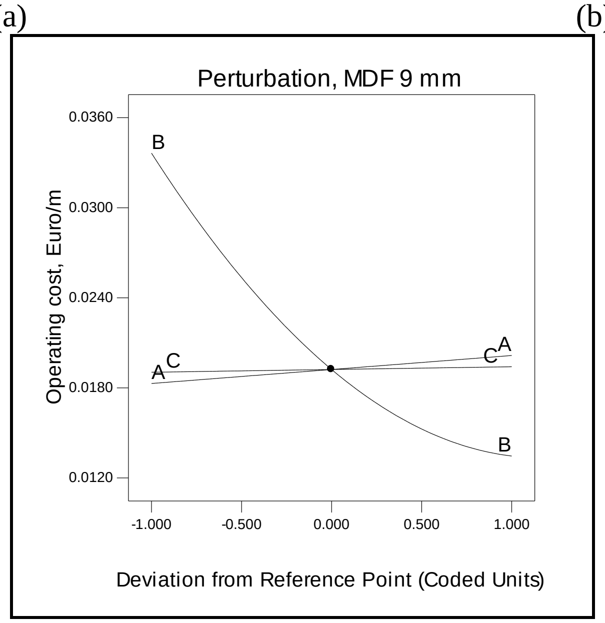
Fig. 9 (a-c) is the perturbation graphs showing the main factors affecting the operating cost. From this graph, it obvious that three factor are affecting the operating cost. The results demonstrated that the main factor affecting the operating cost is the cutting speed as the operating cost reduces remarkably as the cutting speed increases. On the other hand, the laser power and the compressed air are slightly affecting the operating cost and as both the laser power and the compressed air pressure increase the operating cost increases.



(a)



(b)



(c)

Fig. 9: Perturbation plots showing the effect of each factor on the operating cost per meter for the (a) 4 mm thick, (b) 6 mm thick and (c) 9 mm thick.

4. Optimization

Laser cutting is a multi-input and multi-output process that needs to be judged carefully in order to get the most desirable yield of it. Based on the above results and discussion it is clear that there are many factors and their interactions affecting the process, which required an in-depth optimization. To run any optimization it is important to consider the following: the effect of each factor and its interaction with the other factors on the responses, the output of the process (i.e. responses) and finally the quality or the cost of cut section. In the current research, two optimization criteria, in which each factor and response have been given a specific goal, were presented in Table 8. In the first criterion, the quality of the cut section is considered to be an issue, therefore, no restriction were made on the factors. On the second criterion, the cost of the cut section is considered to be more important (i.e. Minimize the cost), therefore, no restrictions were made on the other responses. Solving such multiple response optimization problems using the desirability approach consist of using a technique for combining multiple responses into a dimensionless measure performance called as overall desirability function. The desirability approach consists of transforming of each estimated response into a unit less utilities bounded by $0 < d_i < 1$, where a higher d_i value indicates that response value is more desirable, if $d_i = 0$ this means a completely undesired response or vice versa when $d_i = 1$. This optimization technique has flexibility in assigning weights and importance on each factor and responses [15-17]. The numerical optimization feature in the design expert software package finds a point or more in the factors domain that would maximize the objective function. Table 9-11 list the optimal combinations of process factors for both criteria, which satisfy the desirable goals for each factor and response and look for either, maximize the cut quality (i.e. by improving the output features) or minimize the cutting cost (i.e. by minimizing both the laser power and air pressure as well as maximizing the cutting speed) in an attempt to optimize the laser cutting process of MDF.

Table 8: Criteria for numerical optimization.

Factor or response	First criterion (Quality)		Second criterion (Cost)	
	Goal	Importance	Goal	Importance
Laser power	Is in range	3	Minimize	5
Cutting speed	Is in range	3	Maximize	5
Air pressure	Is in range	3	Minimize	3
Focal position	Is in range	3	Is in range	3
Upper Kerf	Is in range	3	Is in range	3
Lower Kerf	Is in range	3	Is in range	3
Ratio	Target to 1	5	Is in range	3
Roughness	Minimize	5	Is in range	3
Operating cost	Is in range	3	Minimize	5

Table 9: Optimal solution as obtained by Design-Expert for MDF 4 mm.

	No.	A, W	B, mm/min	C, bar	D, mm	Upper kerf, mm	Lower kerf, mm	Ratio	Ra, mm	Cost, €/m	Desirability
1st criterion Quality	1	371.21	2440.28	3.05	-0.6	0.375	0.363	1	3.808	0.0268	1.0000
	2	362.7	2432.56	3.01	-0.5	0.374	0.362	1	3.805	0.0268	1.0000
	3	383.69	2451.55	3.02	-0.82	0.378	0.363	1	3.807	0.0268	1.0000
	4	382.46	2450.93	3.03	-0.79	0.377	0.363	1	3.809	0.0268	1.0000
	5	345.29	2366.19	3.05	-0.25	0.375	0.363	1	3.809	0.0272	1.0000
2nd criterion Cost	1	150	4999.99	3	-2.2	0.341	0.133	2.477	6.276	0.0116	0.9990
	2	150	5000	3	-1.82	0.308	0.126	2.283	6.158	0.0116	0.9990
	3	150	5000	3	-3.6	0.524	0.160	3.531	6.703	0.0116	0.9990
	4	150	5000	3	-3	0.433	0.148	3.014	6.520	0.0116	0.9990
	5	150	5000	3	-3.98	0.592	0.167	3.908	6.818	0.0116	0.9990

4.1 Optimization of 4 mm MDF

Table 9 lists the optimal combinations of process factors and the correspondence responses values for both criteria for 4 mm MDF. It is clear that to achieve high quality cut with predicted ratio of one and Ra = 3.808 μm, a laser power between 345.29 and 383.69 W, cutting speed ranged between 2366.19 mm/min and 2451.55 mm/min with air pressure of about 3 bar and nearly focused beam ranged between -0.82 and -0.25 mm have to be used. These optimal results are in good agreement with the results obtained by Barnekov et al. [6]. On the other hand, if the cost is the main issue, it is demonstrated that, the minimum laser power has to be applied with maximum cutting speed, air pressure of 3 bar and focal point position ranged from -3.98 to -1.82 mm have to be used. In comparison between the two criteria and with regard to the quality of the cut section, the predicted ratio is on average 67.13 % less than the one of the second criterion and theoretically equals to 1, which means the cut edge is square. Also, the cut section roughness for the first criterion is on average 41.38 % smoother than the one of the second criterion. However, the cutting operating cost in the first criterion is 131.72 % higher than the operating cost of the second criterion.

Table 10: Optimal solution as obtained by Design-Expert for MDF 6 mm.

	No.	A, W	B, mm/min	C, bar	D, mm	Upper kerf, mm	Lower kerf, mm	Ratio	Ra, mm	Cost, €/m	Desirability
1st criterion Quality	1	481.1	2126.66	4.97	-1.24	0.453	0.382	1	4.994	0.0318	1.0000
	2	484.09	2180.89	4.29	-2.39	0.543	0.391	1	5.059	0.0311	1.0000
	3	490.97	2141.23	5.43	-1.79	0.477	0.389	1	5.169	0.0318	1.0000
	4	469.04	2003.36	4.03	-0.35	0.437	0.381	1	4.570	0.0330	1.0000
	5	417.2	2240.67	4.01	-0.01	0.408	0.338	1	5.030	0.0296	1.0000
2nd criterion Cost	1	270	5000	4	-2.83	0.343	0.151	2.910	8.365	0.0123	0.9992
	2	270	5000	4	-4	0.466	0.140	3.984	8.614	0.0123	0.9992
	3	270	4999.99	4	-2.91	0.350	0.150	2.973	8.382	0.0123	0.9992
	4	270	4999.99	4	-3.14	0.373	0.149	3.170	8.432	0.0123	0.9992
	5	270	4999.99	4	-4.38	0.512	0.135	4.381	8.692	0.0123	0.9992

4.2 Optimization of 6 mm MDF

Table 10 presents the optimal combinations of process factors and the correspondence responses values for both criteria for 6 mm MDF. It is evident that to accomplish high quality cut with predicted ratio of one and Ra = 4.994 μm a laser power ranged between 417.2 and 490.97 W, cutting speed between 2003.36 and 2240.67 mm/min with air pressure ranged between 4.01 and 5.43 bar and focal point position spanning from -2.39 to -0.01 mm have to be applied. These optimal results are in fair agreement with the results obtained by Barnekov et al. [6], as the focal position is nearly on the surface. Alternatively, if the cost is more important, the optimization results show that, the minimum laser power with maximum cutting speed, air pressure of 4 bar and focal point position ranged from -4.38 to -2.83 mm should to be used. In contrast between the two criteria and concerning the quality of the cut section, the predicted ratio is on average 71.29% less than the ratio obtained in second criterion and in theory equals to 1, which means the cut edge is square. Also, the cut section roughness for the first criterion is on average 41.57 % smoother than the roughness achieved in the second criterion. However, the cutting operating cost in the first criterion is 155.77 % higher than the operating cost of the second criterion.

Table 11: Optimal solution as obtained by Design-Expert for MDF 9 mm.

	No.	A, W	B, mm/min	C, bar	D, mm	Upper kerf, mm	Lower kerf, mm	Ratio	Ra, µm	Cost, €/m	Desirability
1st criterion Quality	1	547.56	2026.67	4.57	-0.29	0.384	0.405	1	5.855	0.0338	1.0000
	2	576.97	2218.95	4.94	-0.05	0.368	0.382	1	5.861	0.0319	1.0000
	3	538.49	2074.52	5.65	-0.12	0.365	0.381	1	6.123	0.0333	1.0000
	4	516.17	2028.72	4.68	-0.1	0.357	0.386	1	5.888	0.0335	1.0000
	5	571.79	2032.49	4.05	-0.45	0.406	0.428	1	5.720	0.0340	1.0000
2nd criterion Cost	1	375	5000	4	-5.43	0.732	0.147	4.356	9.783	0.0129	0.9995
	2	375	4999.99	4	-1.08	0.346	0.204	1.964	7.899	0.0129	0.9995
	3	375	4999.99	4	-4.32	0.633	0.167	3.586	9.298	0.0129	0.9995
	4	375	4999.98	4	-1.74	0.404	0.199	2.213	8.184	0.0129	0.9995
	5	375	4999.99	4	-2.01	0.428	0.197	2.327	8.300	0.0129	0.9995

4.3 Optimization of 9 mm MDF

Table 11 shows the optimal combinations of process factors and the correspondence responses values for both criteria for 9 mm MDF. It is obvious that to accomplish high quality cut with square cut edge in theory and an average Ra = 5.855 µm a laser power ranged between 516.17 and 576.97 W, cutting speed between 2018.95 and 2218.95 mm/min with air pressure ranged between 4.05 and 5.65 bar and focal point position spanning from -0.45 to -0.05 mm have to be used. These optimal results are in fair agreement with the results obtained by Barnekov et al. [6] as the focal position is nearly on the surface. On the other hand, if the cost is more essential, the optimization results show that, the minimum laser power with maximum cutting speed, air pressure of 4 bar and focal point position ranged from -5.43 to -1.08 mm have to be used. In contrast between the two criteria, the predicted ratio obtained in the first criterion is on average 65.39 % less than the ratio obtained in second criterion. Also, the cut section roughness for the first criterion is on average 32.25% smoother than the roughness achieved in the second criterion and in theory equals to 1, which means the cut edge is square. However, the cutting operating cost in the first criterion is 158.14 % higher than the operating cost of the second criterion.

5. Conclusion

The following points can be concluded from this work within the factors limits:

1- The effects of all factors have been established at their different levels.

2- The average upper kerf width decreases as the focal point position, cutting speed and air pressure increase, and it increases as the laser power increases. The focal point position has the main role in affecting the upper kerf.
3- The average lower kerf width decreases as the cutting speed increases and it increases as the laser power increases, it changes slightly as the focal point position increases. The laser power and cutting speed have the main effect on the lower kerf width.
4- The ratio decreases as the focal point position and laser power increase, however, the laser power effect reduces as the material becomes thicker. The ratio increases as the cutting speed increases up to around 3875 mm/min, and then its starts to decreases. Focal point position and the laser power are the principal factors affecting the ratio.
5- The roughness of the cut section decreases as the focal point position and the laser power increase, but the laser power effect reduces when cutting thicker MDF sheets. The roughness increases as the cutting speed and the air pressure increase. All the factors are principally affect the roughness.
6- High quality or economical cut sections could be processed using the tabulated optimal setting.
7- Smother cut sections could be processed, but with increase in the processing operating cost of 131.72 %, 155.77 % and 158.14 % for 4 , 6 and 9 mm MDF respectively.

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