# Effect of process parameters and Optimization of $CO_2$ laser cutting of Ultra High Performance Polyethylene

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## ABSTRACT

The aim of this work is to relate the cutting edge quality parameters (responses) namely: upper kerf, lower kerf, ratio of the upper kerf to lower kerf and cut edge roughness to the process parameters considered in this research and to find out the optimal cutting conditions. The process factors implemented in this research are: laser power, cutting speed and focal point position. Design of experiment (DoE) was used by implementing Box-Behnken design to achieve better cut qualities within existing resources. Mathematical models were developed to establish the relationship between the process parameters and the edge quality parameters. Also, the effects of process parameters on each response were determine. Then, a numerical optimization was performed to find out the optimal process setting at which the quality features are at their desired values. The effect of each factor on the responses was established and the optimal cutting conditions were found.

**Keywords**: $CO_2$ laser cutting, Plastic, Polyethylene, kerf, Roughness, optimization, Design of Experiment.

## 1. Introduction

Lasers are commonly used to cut or machine different types of materials, especially difficult-to-cut materials, in many industrial applications, due to its advantages over the conventional cutting processes. The main advantages of laser cutting are: no tool wear or vibration as it's a non-contact process, low heat input, which results in less distortion and its capability to be numerically controlled [1].

Nowadays, plastic materials are widely used in many applications in many disciplines, for example: biomedical application, cars manufacturing and others. Ultra high molecular weight polyethylene (UHMWPE), also know as high-performance polyethylene is one of the thermoplastic polyethylene. It is characterized with highest impact strength of any thermoplastic presently made [2], with the characterizations that UHMWPE has tolerated it to be utilized in many applications for example, it is been in clinical applications for over 40 years as a successful biomaterial for use in hip, knee, and most recently (since the 1980s), for spine implants [3].

Laser cutting process parameters have been proven to have a major role on the quality features of the cutting edge as reported in [4-8]. Caiazzo et al. [4] have investigated the application of $CO_2$ laser cutting on three thermoplastics, polyethylene (PE), polypropylene (PP) and polycarbonate (PC) with different thicknesses. They have reported that, for all the three plastics, the high cutting speeds are not always synonymous with good process efficiency. However, for all the three polymers, cutting speeds have the highest effect on all quality of the cutting edge and they are higher than those of ferrous and nonferrous metals. Also, they concluded that the employment of powerful $CO_2$ laser is not necessary as couple of hundred Watts is enough to perform the cutting. A three dimensional model of laser cutting process of some plastics has been presented by Atanasov and Baeva [5], with this model it is possible to determine the maximum cutting speed as a function of substrate thickness or laser power. Choudhury and Shirley [6] have investigated $CO_2$ laser cutting of three polymeric materials (PP), (PC) and Polymethyl-methacrylate (PMMA). They reported that the quality of the cut in case of PMMA is much better than those of PP and PC. It was found that the roughness is inversely proportions to laser power, cutting speed and compressed air pressure. However, they mentioned that cutting speed and compressed air pressure have more significant effect on the roughness than the effect of laser power. A preliminary study has been presented by Davim et al [7] to evaluate the effect of the processing parameters on the quality of the cut for several polymeric materials. It was evident that the Heat-affected zone (HAZ) increases with the increase in laser power but it decreases with increase in the cutting speed. Also, they found that the workability of the investigated materials is as follow: PMMA very high, PC high PP high/medium thermosets platics reinforced lower. Davim et al. [8] have evaluated the cutting quality of PMMA using $CO_2$. They reported that HAZ increases with the laser power and decreases with the cutting speed. Also, they found that the surface roughness increases with a decrease in laser power and an increase in cutting speed. Kurt Et al. [9] have concluded that the cutting speed and laser power must be regulated and optimized in order to obtain the desired dimensions and also, to enhance the surface quality and roughness values. Many authors [10-12] have applied DOE to investigate the effect of the factors of a certain process on several outputs and to find the mathematical relationship in order to define the optimal conditions.

In current work response surface methodology (RSM) was applied to build up mathematical relationships between the laser cutting process parameters, laser power, cutting speed and focal point position and the quality of the cut (responses) namely: upper kerf, lower kerf, ratio between upper kerf to lower kerf and surface roughness. Then, the effect of each laser cutting parameter on the responses can be identified through the verified mathematical models. Finally, the desirable and/or optimal cutting conditions can be found by using desirability approach and the developed models.

## 2. Design of Experiment

The experiment was designed based on a three level Box-Behnken design with full replication [13]. Laser power, cutting speed and focal point position are the laser beam cutting (LBC) process input parameters. Table 1 shows LBC parameters and experimental design levels used for the three thicknesses (6, 8 and 10mm) used in this study. RSM was applied to the experimental data using 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 performed 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 [14, 15]. The same statistical software was used to generate the statistical and response plots as well as the optimization.

$$Y = b_o + \sum b_i \chi_i + \sum b_{ii} \chi_{ii}^2 + \sum b_{ij} \chi_i \chi_j \qquad (1)$$

## 3. Experimental Work

UHMWPE, with the properties shown in Table 2, in a sheet form was used as work piece material. The sheet dimensions were 500 x 500 mm with thicknesses of 6, 8 and 10 mm. Trial laser cut runs were performed by varying one of the process factors at-a-time to determine the range of each factor. Full cut, keeping the kerf width, cutting edge striations and dross to a minimum; were the criteria of selecting the working ranges. 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 provided by Mechtronic Industries Ltd and a focusing lens with focal length of 127 mm were used to perform the cut. Compressed air was supplied coaxially as an assist gas with a constant pressure of 3 bar for 6 mm thick and 2 bar for 8 and 10 mm thick. The specimens were cut from the plate for each condition. The specimen shape was designed in order to allow the measurement of the responses in an accurate and easy 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 allow measurement in X-axes and Y-axes. 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 are shown below in Tables 3-5.

## 4. Results and Discussion

### 4.1 Analysis of Variance (ANOVA)

The test for significance of the regression models, test for significance on each model coefficients and the lack of fit test were carried out. Step-wise regression method were selected to select the significant model terms automatically, the resultant ANOVA tables for the reduced quadratic models summarise the analysis of variance of each response and show the significant model terms. In this paper, there are twelve ANOVA tables which are too much to present, therefore, these tables were abstracted to show only the necessary information as shown in Table 6. The same 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. These adequacy measures are in good form as compared the similar ones obtained in [10-12].

#### 4.1.1 Analysis of variance for 6 mm thick model.

The analysis of variance of the 6 mm model indicates that, for the upper kerf model, the main effect of all the factors are the most significant model terms associated with this response. While, for the lower kerf model, the analysis indicates that the main effect of all factors, the quadratic effect of ($A^2$), ($B^2$) and interaction effect between (AB) are the significant model terms. Then, for the ratio model the analysis demonstrated that, the main effect of all factors, the quadratic effect of ($A^2$), ($B^2$)

and the interaction effect between (AB) and (AC) are the significant model terms. Finally, for the roughness model the analysis shows that, the main and the quadratic effects of all factors are the significant model terms. The final mathematical models in terms of coded factors as determined by design expert software are shown below Eqs. 2-5:

$$\text{Upper kerf} = 0.49 + 0.021*A - 0.046*B - 0.18*C \quad (2)$$

$$\text{Lower kerf} = 1.33 + 0.14*A - 0.082*B + 0.057*C + 0.084*AB - 0.074*A^2 - 0.067*B^2 \quad (3)$$

$$\text{Ratio} = 0.37 - 0.031*A - 0.00682*B - 0.17*C - 0.035*AB + 0.018\,AC + 0.024*A^2 + 0.022*B^2 \quad (4)$$

$$Ra = 1.70 - 0.22*A + 0.21*B + 0.012*C + 0.21*A^2 + 0.14*B^2 + 0.63*C^2 \quad (5)$$

**4.1.2 Analysis of variance for 8 mm thick model.**

The analysis of variance of the 8 mm model demonstrates that, for the upper kerf model, the main effect of all the factors and interaction effect between (BC) are the most significant model terms associated with this response. Whereas, for the lower kerf model, the analysis shows that the main effect of all factors, the quadratic effect of ($A^2$), ($B^2$) and ($C^2$) and interaction effect between (AB) are the significant model terms. For the ratio model the analysis demonstrates that, the main effect of all factors, the quadratic effect of ($A^2$), ($B^2$) and ($C^2$) and the interaction effect between (AB) and (AC) and (BC) are the significant model terms. For the roughness model, the analysis indicates that, the main effect of all factors and the quadratic effect of ($A^2$) and ($C^2$) are the significant model terms. The final mathematical models in terms of coded factors as determined by design expert software are shown below Eqs 6-9:

$$\text{Upper kerf} = 0.59 + 0.023*A - 0.033*B - 0.17*C - 0.018*BC \quad (6)$$

$$\text{Lower kerf} = 1.37 + 0.14*A - 0.11*B + 0.14*C + 0.12*AB - 0.048*A^2 - 0.057*B^2 - 0.047*C^2 \quad (7)$$

$$\text{Ratio} = 0.43 - 0.042*A + 0.025*B - 0.19*C - 0.063*AB + 0.033*AC - 0.037*BC + 0.02*A^2 + 0.022*B^2 + 0.042*C^2 \quad (8)$$

$$Ra = 1.82 - 0.22*A + 0.18*B + 0.037*C + 0.25*A^2 + 0.63*C^2 \quad (9)$$

### 4.1.3 Analysis of variance for 10 mm thick model.

The analysis of variance of the 10 mm model reveals that, for the upper kerf model, the main effect of all the factors are the most significant model terms associated with this response. Whereas, for the lower kerf model, the analysis shows that the main effect of all factors and interaction effect between (AB) are the significant model terms. For the ratio model the analysis demonstrates that, the main effect of all factors, the quadratic effect of ($B^2$) and the interaction effect between (AB) are the significant model terms. Finally, for the roughness model the analysis indicates that, the main effect of all factors and the interaction effect between (AC) and the quadratic effect of ($A^2$) and ($C^2$) are the significant model terms. The final mathematical models in terms of coded factors as determined by design expert software are shown below Eqs 10-13:

$$\text{Upper kerf} = 0.71 + 0.0096*A - 0.017*B - 0.15*C \quad (10)$$

$$\text{Lower kerf} = 1.43 + 0.17*A - 0.12*B + 0.086*C + 0.15*AB \quad (11)$$

$$\text{Ratio} = 0.49 - 0.062*A + 0.042*B - 0.14*C - 0.069\,AB + 0.040\,B^2 \quad (12)$$

$$Ra = 2.24 - 0.27*A + 0.26*B - 0.0086*C + 0.058\,AC + 0.11\,A^2 + 0.90\,C^2 \quad (13)$$

### 4.2 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 taken 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 error for all the four responses are within resalable agreement, therefore the models are valid.

### 4.3 Effect of Process Factors on the Responses

#### 4.3.1 Upper kerf

It is evident from Fig. 1 that the Focal point position has the major effect on the upper kerf and then the laser power and cutting speed. However, the upper kerf increases as the focal position and the cutting speed decreases while it increase as the laser power increases. In fact, this is due to that when a defocused beam is being used the laser power would spread on the surface onto a wider area, as the beam will become wider at the top of the specimen, causing the upper kerf to increase. Also, when using slow cutting speed more heat would be introduced to the specimen and then more materials will be melted and ejected causing the upper kerf to increase. In the case of laser power effect, the upper kerf would increase as a consequence of increasing the laser power due to the increase in the heat input following the increase in the laser power. These results are in good agreement with the results obtained by Caiazzo et al. [4]. The percentages of change in the upper kerf as a result of changing each factor from its lowest value to its highest value while keeping the other factors at their centre values are as follows (the percentages are for 6 mm, 8 mm and 10 mm thick respectively): (i) Changing focal position would result in a decrease of 54.64%, 44.78% and 34.61%. (ii) Changing the cutting speed would result in a decrease of 17.11%, 10.75% and 4.74%. (iii) Changing the laser power would result in an increase of 8.96%, 8.23% and 2.73%. Fig. 2 contour plots showing the effect of focal position and cutting speed on the upper kerf for the three thicknesses.

#### 4.3.2 Lower kerf

It is apparent from Fig. 3 that all the three factors have a major role on the lower kerf with the following order laser power, cutting speed and focal position. However, upper kerf increases as the laser power and focal increases while it decreases as the cutting speed increases. This is due to that when a defocused beam is being used the laser power would spread on the bottom surface onto a wider area, as the beam is becoming wider at the bottom of the specimen, causing the lower kerf to increase. Also, by using slow cutting speed more heat would be brought in to the specimen and then more materials will be melted and ejected causing the lower kerf to increase. In the case of laser power effect, the lower kerf would remarkably increase as the laser power increases due to the increase in the heat input following this raising in the beam power. The percentages of change in the lower kerf as a result of changing each factor from its lowest value to its highest value whilst maintaining the other factors at their centre values are as follows (the percentages are for 6 mm, 8 mm and 10 mm thick respectively): (i) Changing focal position would result in an increase of 8.97%, 23.10% and 12.83%. (ii) Changing the cutting speed would result in a decrease of 12.20%, 15.56% and 15.38%. (iii) Changing the laser power would result in an increase of 25.49%, 23.84% and 27.32%. Fig. 4 contour plots presents the effect of cutting speed and laser power on the lower kerf for the three thicknesses.

#### 4.3.3 Ratio of the upper kerf to the lower kerf

It is obvious from Fig. 5 that the focal point position has the key role on the ratio between the upper kerf to the lower kerf and then the laser power and cutting speed but with less effect. In the case of cutting speed effect, the ratio would increase as the cutting speed increases, this increase is higher for the thicker UHMWPE and becomes not notable for the thinner UHMWPE. The percentages of change in the ratio as a result of manipulating each factor from its lowest value to its highest value while keeping the other factors at their centre levels are as follows (the percentages are for 6 mm, 8 mm and 10 mm respectively): (i) Changing focal position would result in a decrease of 61.70%, 57.53% and 43.91%. (ii) Changing laser power would result in a decrease of 14.46%, 17.19% and 22.49%. (iii) Changing the cutting speed would result in an increase of 3.39%, 11.60% and 17.24%. Fig. 6 demonstrates the interaction effect between the laser power and cutting speed on the ratio between the upper kerf and lower kerf. It is clear from Fig. 6 a-c that, by using the highest cutting speed with low laser power, which would result in reducing the operating cost, a higher ratio values (i.e. ratio values closer to 1 which would lead to a plane-parallel cut faces, in other words cuts with upper kerf width approximately equal to the lower kerf width) would be achieved as compared with the case of applying lowest cutting speed, yet this is valid only up to certain thresholds of laser power, which are around 1000 W, 1250 W and 1380 W for the thicknesses of 6 mm, 8 mm and 10 mm respectively. Above these thresholds the higher values of ratios can be obtained only if the slowest cutting speed is being applied of course in conjunction with higher laser power levels, but these would increase the operating cost. These results support the results reported by Caiazzo et al. [4] as the high cutting speeds are not at all times synonymous with good cutting efficiency.

#### 4.3.4 Roughness

It is clear from Fig. 7 that all the three factors have a major effect on the roughness of the cut surface the same has been outlined in [4 and 6]. The results show that the roughness is inversely proportions to laser power which is in agreement with the results reported in [6 and 8]. Also, it was found that the roughness is proportions to cutting speed, which is in agreement with the result reported in [8] and disagrees with results reported in [6]. However, this disagreement may be due to the differences in the properties of the plastic material. In the case of focal point position, the roughness decreases as the focal position increases up to a certain point (when the focal position is approximately at half of the thickness) and then it starts to increase. Therefore, when the focal point is located at centre of the material to be cut, the roughness would be a minimum value given that all the other factors are at their centre levels. The percentages of change in the roughness as a result of changing each factor from its lowest value to its highest value whilst maintaining the other factors at their centre values are as follows (the percentages are for 6 mm, 8 mm and 10 mm thick respectively): (i) Changing cutting speed would result in an increase of 26.24%, 21.90% and 26.47%. (ii) Changing the laser power would result in a decrease of 20.75%, 18.86% and 20.72%. (iii) Changing the focal point position from its lowers level to its centre level would result in a decrease of 26.57%, 24.71% and 28.90%. However, by changing the focal point position from its centre level to its highest level would result in an increase of 37.64%, 36.84% and 39.89%. Fig. 8 contour plots presents the effect of cutting speed and laser power on the roughness for the 10 mm thick UHMWPE at three levels of focal position. It is clear that when F = -5.5 mm ( Fig. 8-b) the roughness would be less as compared with the roughness values obtained using the same levels of laser power and cutting speed, but using F = -7 mm and F = -4 mm as in Fig. 8 a and c. In contrast, to meet the end-user’s cutting requirements it is a compromising matter as to perform the cutting operation from a quality point of view or from cost point of view. Therefore, an optimization of the cutting process is essential.

## 5. Optimization

Actually, to plan and fabricate parts by laser cutting process and considering only the quality of the final cut surface sometimes this scenario has an influence on the cost of that part or vice versa. Also, laser power and cutting speed as well as focal point position have to be monitored and optimized to facilitate the desirable surface quality or kerfs dimensions, as reported by Kurt et al. [9]. Therefore, it’s better to find out the optimal cutting conditions at which the desirable quality or cost saving of the cutting can be achieved. In fact, as the models have been developed and checked for their adequacy, optimization criteria can be set to find out the optimum cutting conditions. Hence, two optimization criteria have been introduced as in Table 8 for numerical optimization. The first one is to find out the optimal cutting conditions that would lead to the highest quality. On the other hand, the second criterion is to find out the optimal cutting conditions which would minimize the operating cost by minimizing the laser power and maximizing the cutting speed. The optimal solutions that fulfil these criteria for all thicknesses are presented in Tables 9-11.

**5.1 Optimization of 6 mm UHMWPE**

Table 9 shows the optimal conditions of process factors and the correspondence responses values for both criteria for 6 mm UHMWPE. It is clear that to achieve high quality cut with predicted ratio as close as possible to one and Ra ≈ 1.743 μm, the laser power has to be between 1256.79 W and 1268.87 W, along with the slowest level of cutting speed of 1000 mm/min and focal point position of -3.24 mm have to be used. On the other hand, if reducing the operating cost is more important, it is verified that, the minimum laser power has to be applied with maximum cutting speed of 1750 mm/min and focal point position ranged from -2.51 to -1.5 mm have to be used. In comparison between the two criteria and with regard to the quality of the cut section, the cut section roughness for the first criterion is on average 44% smoother than the one of the second criterion, this improvement in the surface quality support the conclusion made by Kurt [9]. Although, the cutting cost is certainly higher in the first criterion as the laser power is higher along with slower cutting speed, but the quality of the cut section is better if the optimal factors combinations in the first criterion are used.

**5.2 Optimization of 8 mm UHMWPE**

Table 10 presents the optimal setting of process factors and the matching responses values for both criteria for 8 mm UHMWPE. It is obvious that to obtain the superior quality cut with predicted ratio as close as possible to one and Ra ≈ 1.853 μm, the laser power has to be between 1293.4 W and 1322.45 W with the slowest level of cutting speed of 800 mm/min and focal point position of -5.48 mm have to be applied. Alternatively, if the reduction in the cutting cost is essential, it is confirmed that, the minimum laser power of 900 W has to be applied with maximum cutting speed of 1400 mm/min and focal point position ranged from -4.74 mm to -3.43 mm have to be used. In contrast between the two criteria and with regard to the quality of the cut section, the cut section roughness for the first criterion is on average 33% smoother than the one of the second criterion, which is in agreement with Kurt [9].

### 5.3 Optimization of 10 mm UHMWPE

Table 11 lists the optimal setting of process factors and the corresponding responses values for both criteria for 10 mm UHMWPE. It is apparent that to get the greatest quality cut with predicted ratio close to one and Ra ≈ 2.050 μm, the highest level of laser power of 1450 W has to used along with the slowest level of cutting speed of 700 mm/min and focal point position of around -6.31 mm have to be applied. Instead, if minimizing the cost is crucial, it is demonstrated that, the minimum laser power of 1100 W has to be used with maximum cutting speed of 1150 mm/min and focal point position ranged from -5.76 to -4.96 mm have to be used. In contrast between the two criteria and with reference to the quality of the cut section, the cut section roughness for the first criterion is on average 41% smoother than the one of the second criterion.

## 6. Conclusions

The following conclusion can be drawn from this investigation within the factors limits and only applicable for experiment setup considered in this study and for the specified material:

1- All the investigated factors have a potential effect on the responses with different levels.

2- Cutting UHMWPE with laser cutting required high power ranged from 800 W to 1450 W depending on the material thickness.

3- The upper kerf decreases as the focal position and the cutting speed increase, and it increases as the laser power increases. The focal position has the major role on the upper kerf.

4- The lower kerf increases as the laser power and focal position increase, and it decreases as the cutting speed increases.

5- The ratio decreases as the focal position and laser power increase, and it increases as the cutting speed increases. The focal position has the main effect on the ratio.

6- The roughness decreases as the focal point increases from its lowest level till its central level and then it increases as the focal starts to increase above its central level. The roughness decreases as the laser power increases and it increases as the cutting speed increases.

7- Higher cutting speed does not always improve the efficiency of the laser cutting process.

8- The optimal conditions for UHMWPE 6 mm thick are laser power between 1258.25 and 1268.87 W, cutting speed of 1000 mm/min and focal position of -3.24 mm if the quality is an issue, but if the cost is more important the optimal cutting conditions are laser power of 800 W, cutting speed of 1750 mm/min and focal position ranged between -2.51 and -1.39 mm.

9- The optimal conditions for UHMWPE 8 mm thick are laser power between 1293.4 and 1322.45 W, cutting speed of 800 mm/min and focal position between -5.51 and -5.46 mm if the quality is a matter of interest, but if the cost is more important the optimal cutting conditions are laser power of 900 W, cutting speed of 1400 mm/min and focal position ranged between -4.74 and -3.43 mm.

10- The optimal conditions for UHMWPE 10 mm thick are laser power between 1436 and 1450 W, cutting speed between 700 and 704.76 mm/min and focal position between -6.31 and -6.23 mm if the quality is desirable, but if the cost is more important the optimal cutting conditions are laser power of 1100 W, cutting speed of 1150 mm/min and focal position ranged between -5.76 and -4.96 mm.

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**References:**

[1] J. Powell, $CO_2$ Laser Cutting, 2nd Edition, Springer-Verlag Berlin Heidelberg, New York, (1998).

[2] http://en.wikipedia.org/wiki/Ultra_high_molecular_weight_polyethylene(accessed on September 2009).

[3] Kurtz Steven M., the UHMWPE Handbook, Academic Press, New York, (2004) ISBN: 0124298516.

[4] F. Caiazzo, F. Curico, G. Daurelio, F. M. C. Minutolo, Laser cutting of different polymetric plastics (PE, PP and PC) by a $CO_2$ laser beam, Journal of Materials Processing Technology, 159 (2005) 279-285.

[5] P. A. Atanasov and M. G. Baeva, CW $CO_2$ laser cutting of plastics, 3092 (1997) 772-775.

[6] I. A. Choudhury and S. Shirley, laser cutting of polymeric materials: An experimental investigation, journal of Optics and Laser Technology, 42 (2010) 503-508.

[7] J. P. Davim, N. Barricas, M. Conceicao and C. Oliverira, Some experimental studies on $CO_2$ laser cutting quality of polymeric materials, Journal of Materials Processing Technology, 198 (2008) 99-104.

[8] J. P. Davim, C. Oliveira, N. Barricas and M. Conceicão, Evaluation of cutting quality of PMMA using $CO_2$ lasers, International Journal of Advanced Manufacturing Technology, 35 (2008) 875-879.

[9] M. Kurt, Y. Kaynak, E. Bagei, H. Demirer and M. Kurt, Dimensional analyses and surface quality of laser cutting process for engineering plastics, Inter. J. of Manuf. Technology, 41 (2009) 259-267.

[10] A.G. Olabi, G. Casalino, K.Y. Benyounis, A. Rotondo, Minimisation of the residual stress in the heat affected zone by means of numerical methods, Materials & Design, 28 (8) ( 2007) 2295-2302.

[10] H. Naceur, S. Ben-Elechi, J.L. Batoz, C. Knopf-Lenoir, Response surface methodology for the rapid design of aluminum sheet metal forming parameters, Materials & Design, 29 (4) (2008) 781-790.

[11] F. M. Shuaeib, A. M. S. Hamouda, S. V. Wong, R. S. Radin Umar, M. M. H. Megat Ahmed, A new motorcycle helmet liner material: The finite element simulation and design of experiment optimization, Materials & Design, 28 (1) (2007) 182-195.

[12] Design-Expert software, v7, user’s guide, Technical manual, Stat-Ease Inc., Minneapolis, MN, 2000.

[13] D.C. Montgomery, Design and Analysis of Experiments, 2nd Ed, John Wiley & Sons, New York, (1984).

[14] A. I. Khuri and J.A. Cornell, *Response Surfaces Design and Analysis*, 2nd ed, Marcel Dekker, New York, (1996).

Table 1: Process variables and experimental design levels.

| Parameter | Code | Unit | Levels | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | -1 | | | 0 | | | +1 | | |
| | | | Thickness, mm | | | Thickness, mm | | | Thickness, mm | | |
| | | | 6 | 8 | 10 | 6 | 8 | 10 | 6 | 8 | 10 |
| Laser power | A | kW | 800 | 900 | 1100 | 1050 | 1150 | 1275 | 1300 | 1400 | 1450 |
| Cutting speed | B | mm/min | 1000 | 800 | 700 | 1375 | 1100 | 925 | 1750 | 1400 | 1150 |
| Focal point position | C | mm | -4 | -6 | -7 | -2.5 | -4.5 | -5.5 | -1 | -3 | -4 |

Table 2: Mechanical and thermal properties of UHMWPE.

| **Property** | **Units** | **Test Method** | **UHMWPE** |
|---|---|---|---|
| Density | $Kg/m^3$ | ISO 1183 | 930 |
| Tensile Yield Strength | MPa | ISO 527 | 17 |
| Tensile Modulus | MPa | ISO 527 | 700 |
| Melting point | °C | ISO 3146 | 135-138 |
| Coefficient of Linear Thermal Expansion | $K^{-1} * 10^{-4}$ | ISO 11359 | 2 |
| Thermal Conductivity | W/(m*K) | ISO 52612 | 0.4 |

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: Focal position, mm | Upper kerf, mm | Lower kerf, mm | Ratio | Ra, μm |
| 1 | 10 | 800 | 1000 | -2.5 | 0.516 | 1.242 | 0.416 | 2.233 |
| 2 | 13 | 1300 | 1000 | -2.5 | 0.570 | 1.361 | 0.419 | 1.603 |
| 3 | 15 | 800 | 1750 | -2.5 | 0.420 | 0.866 | 0.485 | 2.339 |
| 4 | 3 | 1300 | 1750 | -2.5 | 0.461 | 1.321 | 0.349 | 2.054 |
| 5 | 7 | 800 | 1375 | -4 | 0.649 | 1.047 | 0.620 | 2.645 |
| 6 | 8 | 1300 | 1375 | -4 | 0.680 | 1.291 | 0.527 | 2.178 |
| 7 | 5 | 800 | 1375 | -1 | 0.274 | 1.154 | 0.238 | 2.867 |
| 8 | 2 | 1300 | 1375 | -1 | 0.317 | 1.470 | 0.216 | 2.475 |
| 9 | 6 | 1050 | 1000 | -4 | 0.718 | 1.263 | 0.569 | 2.274 |
| 10 | 4 | 1050 | 1750 | -4 | 0.628 | 1.147 | 0.548 | 2.876 |
| 11 | 12 | 1050 | 1000 | -1 | 0.344 | 1.351 | 0.255 | 2.089 |
| 12 | 11 | 1050 | 1750 | -1 | 0.273 | 1.228 | 0.222 | 2.640 |
| 13 | 14 | 1050 | 1375 | -2.5 | 0.509 | 1.320 | 0.385 | 1.561 |
| 14 | 16 | 1050 | 1375 | -2.5 | 0.498 | 1.355 | 0.367 | 1.933 |
| 15 | 17 | 1050 | 1375 | -2.5 | 0.500 | 1.333 | 0.375 | 1.718 |
| 16 | 9 | 1050 | 1375 | -2.5 | 0.483 | 1.333 | 0.363 | 1.601 |
| 17 | 1 | 1050 | 1375 | -2.5 | 0.490 | 1.339 | 0.366 | 1.682 |

Table 4: Design matrix and experimentally recorded responses for thickness 8 mm.

| Std | Run | Factors | | | Responses | | | |
|---|---|---|---|---|---|---|---|---|
| | | A: Laser power, W | B: Cutting speed, mm/min | C: Focal position, mm | Upper kerf, mm | Lower kerf, mm | Ratio | Ra, μm |
| 1 | 13 | 900 | 800 | -4.5 | 0.574 | 1.368 | 0.420 | 2.313 |
| 2 | 1 | 1400 | 800 | -4.5 | 0.662 | 1.423 | 0.465 | 1.683 |
| 3 | 17 | 900 | 1400 | -4.5 | 0.519 | 0.862 | 0.601 | 2.399 |
| 4 | 3 | 1400 | 1400 | -4.5 | 0.561 | 1.413 | 0.397 | 2.104 |
| 5 | 4 | 900 | 1100 | -6 | 0.755 | 1.000 | 0.756 | 2.705 |
| 6 | 8 | 1400 | 1100 | -6 | 0.774 | 1.288 | 0.601 | 2.298 |
| 7 | 9 | 900 | 1100 | -3 | 0.408 | 1.294 | 0.315 | 2.987 |
| 8 | 11 | 1400 | 1100 | -3 | 0.445 | 1.528 | 0.291 | 2.595 |
| 9 | 5 | 1150 | 800 | -6 | 0.776 | 1.238 | 0.627 | 2.398 |
| 10 | 10 | 1150 | 1400 | -6 | 0.756 | 1.016 | 0.744 | 2.766 |
| 11 | 7 | 1150 | 800 | -3 | 0.470 | 1.484 | 0.316 | 2.158 |
| 12 | 15 | 1150 | 1400 | -3 | 0.379 | 1.333 | 0.284 | 2.720 |
| 13 | 2 | 1150 | 1100 | -4.5 | 0.600 | 1.370 | 0.438 | 1.681 |
| 14 | 6 | 1150 | 1100 | -4.5 | 0.578 | 1.372 | 0.421 | 1.933 |
| 15 | 14 | 1150 | 1100 | -4.5 | 0.583 | 1.387 | 0.420 | 1.798 |
| 16 | 16 | 1150 | 1100 | -4.5 | 0.593 | 1.362 | 0.435 | 1.701 |
| 17 | 12 | 1150 | 1100 | -4.5 | 0.586 | 1.370 | 0.427 | 1.762 |

Table 5: Design matrix and experimentally recorded responses for thickness 10 mm.

| Std | Run | Factors | | | Responses | | | |
|---|---|---|---|---|---|---|---|---|
| | | A: Laser power, W | B: Cutting speed, mm/min | C: Focal position, mm | Upper kerf, mm | Lower kerf, mm | Ratio | Ra, μm |
| 1 | 12 | 1100 | 700 | -5.5 | 0.730 | 1.443 | 0.506 | 2.376 |
| 2 | 9 | 1450 | 700 | -5.5 | 0.736 | 1.593 | 0.462 | 1.798 |
| 3 | 2 | 1100 | 1150 | -5.5 | 0.688 | 0.927 | 0.742 | 2.950 |
| 4 | 16 | 1450 | 1150 | -5.5 | 0.706 | 1.676 | 0.421 | 2.344 |
| 5 | 14 | 1100 | 925 | -7 | 0.851 | 1.226 | 0.694 | 3.521 |
| 6 | 6 | 1450 | 925 | -7 | 0.878 | 1.459 | 0.602 | 2.912 |
| 7 | 8 | 1100 | 925 | -4 | 0.554 | 1.418 | 0.391 | 3.438 |
| 8 | 10 | 1450 | 925 | -4 | 0.580 | 1.659 | 0.349 | 3.059 |
| 9 | 4 | 1275 | 700 | -7 | 0.874 | 1.392 | 0.628 | 2.949 |
| 10 | 3 | 1275 | 1150 | -7 | 0.846 | 1.193 | 0.709 | 3.427 |
| 11 | 11 | 1275 | 700 | -4 | 0.580 | 1.601 | 0.362 | 2.875 |
| 12 | 17 | 1275 | 1150 | -4 | 0.543 | 1.281 | 0.424 | 3.370 |
| 13 | 15 | 1275 | 925 | -5.5 | 0.716 | 1.476 | 0.485 | 2.178 |
| 14 | 1 | 1275 | 925 | -5.5 | 0.715 | 1.473 | 0.485 | 2.330 |
| 15 | 5 | 1275 | 925 | -5.5 | 0.719 | 1.526 | 0.471 | 2.243 |
| 16 | 13 | 1275 | 925 | -5.5 | 0.690 | 1.463 | 0.471 | 2.147 |
| 17 | 7 | 1275 | 925 | -5.5 | 0.704 | 1.476 | 0.477 | 2.215 |

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

| Thickness | Response | $SS_{-model}$ | DF | Lack of Fit | Prob. >F Model | $R^2$ | Adj- $R^2$ | Pre- $R^2$ |
|---|---|---|---|---|---|---|---|---|
| 6 | Upper kerf | 0.29 | 13 | Not Sig. | < 0.0001 (Sig.) | 0.9951 | 0.9940 | 0.9916 |
| | Lower kerf | 0.31 | 6 | Not Sig. | < 0.0001 (Sig.) | 0.9697 | 0.9515 | 0.8569 |
| | Ratio | 0.24 | 7 | Not Sig. | < 0.0001 (Sig.) | 0.9950 | 0.9911 | 0.9741 |
| | Ra | 2.836 | 6 | Not Sig. | < 0.0001 (Sig.) | 0.9126 | 0.8602 | 0.7168 |
| 8 | Upper kerf | 0.25 | 4 | Not Sig. | < 0.0001 (Sig.) | 0.9895 | 0.9859 | 0.9757 |
| | Lower kerf | 0.51 | 7 | Not Sig. | < 0.0001 (Sig.) | 0.9884 | 0.9794 | 0.9144 |
| | Ratio | 0.35 | 9 | Not Sig. | < 0.0001 (Sig.) | 0.9987 | 0.9970 | 0.9897 |
| | Ra | 2.68 | 5 | Not Sig. | < 0.0001 (Sig.) | 0.9166 | 0.8787 | 0.7689 |
| 10 | Upper kerf | 0.18 | 3 | Not Sig. | < 0.0001 (Sig.) | 0.9951 | 0.9940 | 0.9932 |
| | Lower kerf | 0.50 | 4 | Not Sig. | < 0.0001 (Sig.) | 0.8882 | 0.8510 | 0.7243 |
| | Ratio | 0.22 | 5 | Not Sig.* | < 0.0001 (Sig.) | 0.9567 | 0.9371 | 0.8298 |
| | Ra | 4.69 | 6 | Not Sig. | < 0.0001 (Sig.) | 0.9921 | 0.9874 | 0.9742 |

* Not Significant at $\alpha = 0.001$.

Table 7: Confirmation experiments.

| Thick-ness | Exp. No. | Factors | | | Values | Responses | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | A | B | C | | Upper kerf | Lower kerf | Ratio | Roughness |
| 6 | 1 | 1261.7 | 1000 | -3.24 | Actual | 0.634 | 1.450 | 0.437 | 1.774 |
| | | | | | Predicted | 0.644 | 1.309 | 0.498 | 1.743 |
| | | | | | Error % | -1.577 | 9.749 | -13.927 | 1.747 |
| | 2 | 800 | 1750 | -1.35 | Actual | 0.267 | 0.879 | 0.303 | 2.590 |
| | | | | | Predicted | 0.283 | 0.922 | 0.337 | 2.869 |
| | | | | | Error % | -6.072 | -4.868 | -11.053 | -10.755 |
| 8 | 1 | 1312.8 | 800 | -5.48 | Actual | 0.792 | 1.406 | 0.563 | 1.801 |
| | | | | | Predicted | 0.738 | 1.307 | 0.552 | 1.853 |
| | | | | | Error % | 6.795 | 7.054 | 1.967 | -2.864 |
| | 2 | 900 | 1400 | -4.5 | Actual | 0.572 | 0.904 | 0.633 | 2.167 |
| | | | | | Predicted | 0.533 | 0.891 | 0.600 | 2.463 |
| | | | | | Error % | 6.883 | 1.416 | 5.262 | -13.649 |
| 10 | 1 | 1450 | 700 | -6.31 | Actual | 0.810 | 1.619 | 0.500 | 2.147 |
| | | | | | Predicted | 0.819 | 1.523 | 0.571 | 2.050 |
| | | | | | Error % | -1.161 | 5.930 | -14.186 | 4.518 |
| | 2 | 1100 | 1150 | -5.5 | Actual | 0.705 | 0.921 | 0.766 | 2.560 |
| | | | | | Predicted | 0.685 | 0.988 | 0.706 | 2.882 |
| | | | | | Error % | 2.809 | -7.321 | 7.783 | -12.587 |

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 |
| 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 | Maximize | 5 | Is in range | 3 |
| Roughness | Minimize | 5 | Is in range | 3 |

Table 9: Optimal solution as obtained by Design-Expert for UHMWPE 6 mm.

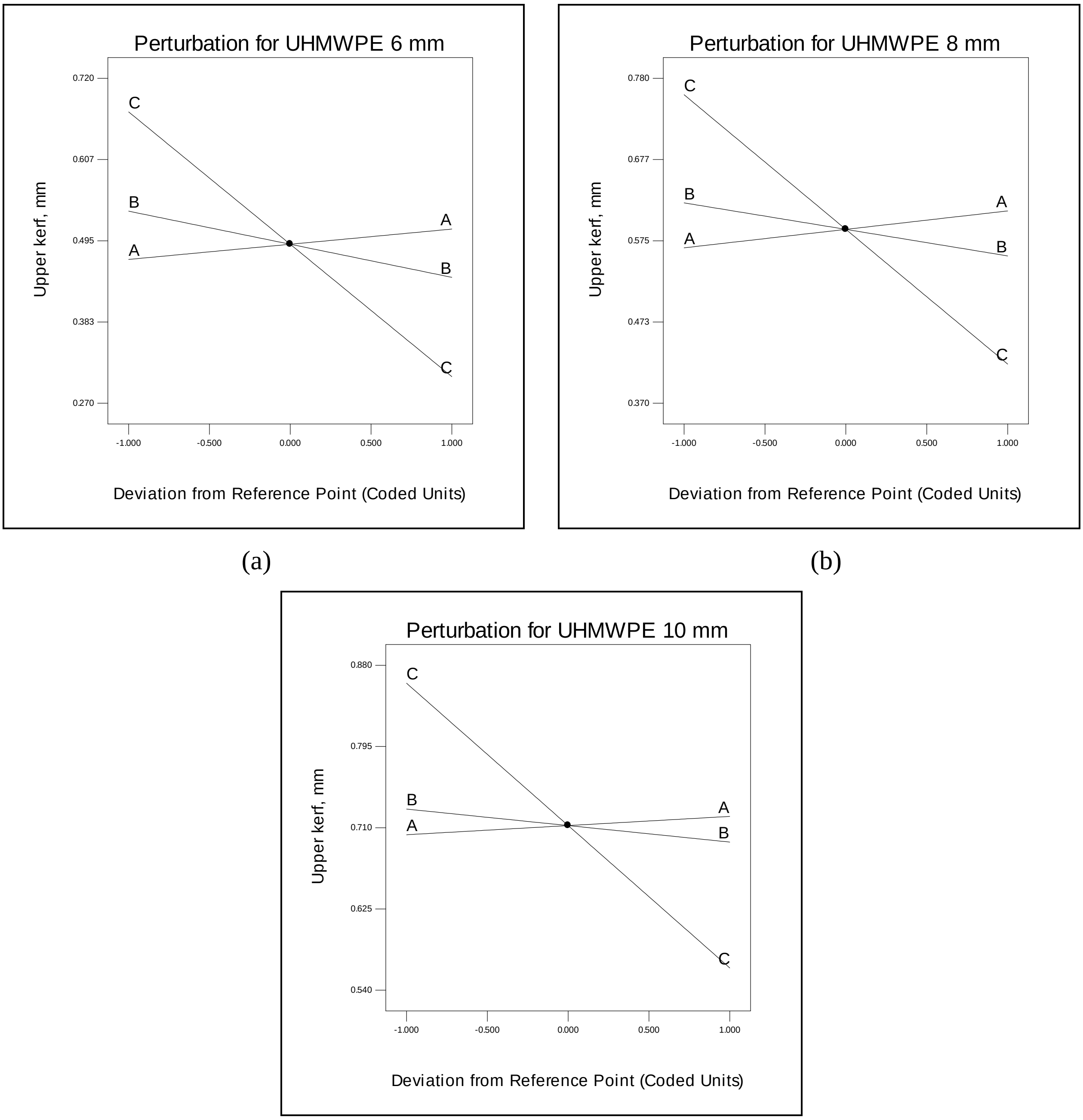
| | No. | A, W | B, mm/min | C, mm | Upper kerf, mm | Lower kerf, mm | Ratio | Ra, µm | Desirability |
|---|---|---|---|---|---|---|---|---|---|
| 1st criterion Quality | 1 | 1261.74 | 1000 | -3.24 | 0.644 | 1.309 | 0.498 | 1.743 | 0.7753 |
| | 2 | 1266.58 | 1000 | -3.24 | 0.645 | 1.307 | 0.499 | 1.746 | 0.7753 |
| | 3 | 1258.25 | 1000 | -3.23 | 0.643 | 1.310 | 0.497 | 1.738 | 0.7753 |
| | 4 | 1268.87 | 1000 | -3.24 | 0.645 | 1.307 | 0.498 | 1.745 | 0.7753 |
| | 5 | 1256.79 | 1000 | -3.21 | 0.640 | 1.311 | 0.494 | 1.728 | 0.7751 |
| 2nd criterion Cost | 1 | 800 | 1750 | -2.32 | 0.402 | 0.885 | 0.457 | 2.503 | 1.0000 |
| | 2 | 800 | 1750 | -1.39 | 0.287 | 0.920 | 0.342 | 2.847 | 1.0000 |
| | 3 | 800 | 1750 | -2.51 | 0.424 | 0.878 | 0.480 | 2.493 | 1.0000 |
| | 4 | 800 | 1750 | -1.84 | 0.343 | 0.903 | 0.398 | 2.619 | 1.0000 |
| | 5 | 800 | 1750 | -1.5 | 0.300 | 0.916 | 0.355 | 2.782 | 1.0000 |

Table 10: Optimal solution as obtained by Design-Expert for UHMWPE 8 mm.

| | No. | A, W | B, mm/min | C, mm | Upper kerf, mm | Lower kerf, mm | Ratio | Ra, μm | Desirability |
|---|---|---|---|---|---|---|---|---|---|
| 1st criterion Quality | 1 | 1312.77 | 800 | -5.48 | 0.738 | 1.307 | 0.552 | 1.853 | 0.7024 |
| | 2 | 1310.97 | 800 | -5.48 | 0.738 | 1.307 | 0.552 | 1.853 | 0.7024 |
| | 3 | 1315.59 | 800 | -5.49 | 0.739 | 1.304 | 0.554 | 1.861 | 0.7024 |
| | 4 | 1322.45 | 800 | -5.46 | 0.737 | 1.307 | 0.551 | 1.847 | 0.7024 |
| | 5 | 1293.4 | 800 | -5.51 | 0.739 | 1.306 | 0.554 | 1.860 | 0.7021 |
| 2nd criterion Cost | 1 | 900 | 1400 | -4.5 | 0.533 | 0.891 | 0.600 | 2.463 | 1 |
| | 2 | 900 | 1400 | -3.43 | 0.399 | 0.965 | 0.437 | 2.811 | 1.0000 |
| | 3 | 900 | 1400 | -4.74 | 0.562 | 0.868 | 0.642 | 2.473 | 1.0000 |
| | 4 | 900 | 1400 | -3.64 | 0.425 | 0.954 | 0.465 | 2.693 | 1.0000 |
| | 5 | 900 | 1400 | -4.24 | 0.500 | 0.913 | 0.557 | 2.489 | 1.0000 |

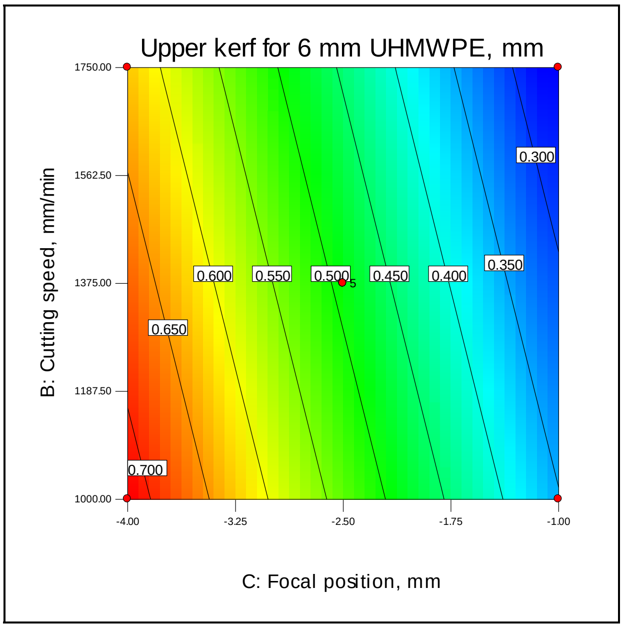
Table 11: Optimal solution as obtained by Design-Expert for UHMWPE 10 mm.

| | No. | A, W | B, mm/min | C, mm | Upper kerf, mm | Lower kerf, mm | Ratio | Ra, µm | Desirability |
|---|---|---|---|---|---|---|---|---|---|
| 1st criterion Quality | 1 | 1450 | 700 | -6.31 | 0.819 | 1.523 | 0.571 | 2.050 | 0.6940 |
| | 2 | 1450 | 700 | -6.26 | 0.815 | 1.526 | 0.567 | 2.025 | 0.6937 |
| | 3 | 1450 | 701.21 | -6.23 | 0.812 | 1.528 | 0.564 | 2.009 | 0.6919 |
| | 4 | 1435.99 | 700 | -6.29 | 0.817 | 1.522 | 0.569 | 2.048 | 0.6915 |
| | 5 | 1449.99 | 704.76 | -6.3 | 0.818 | 1.524 | 0.568 | 2.051 | 0.6891 |
| 2nd criterion Cost | 1 | 1100 | 1150 | -5.5 | 0.685 | 0.988 | 0.706 | 2.882 | 1 |
| | 2 | 1100 | 1150 | -5.76 | 0.712 | 0.973 | 0.730 | 2.922 | 1.0000 |
| | 3 | 1100 | 1150 | -5.28 | 0.664 | 1.001 | 0.686 | 2.892 | 1.0000 |
| | 4 | 1100 | 1150 | -4.96 | 0.631 | 1.019 | 0.656 | 2.976 | 1.0000 |
| | 5 | 1100 | 1150 | -5.07 | 0.642 | 1.013 | 0.666 | 2.938 | 1.0000 |

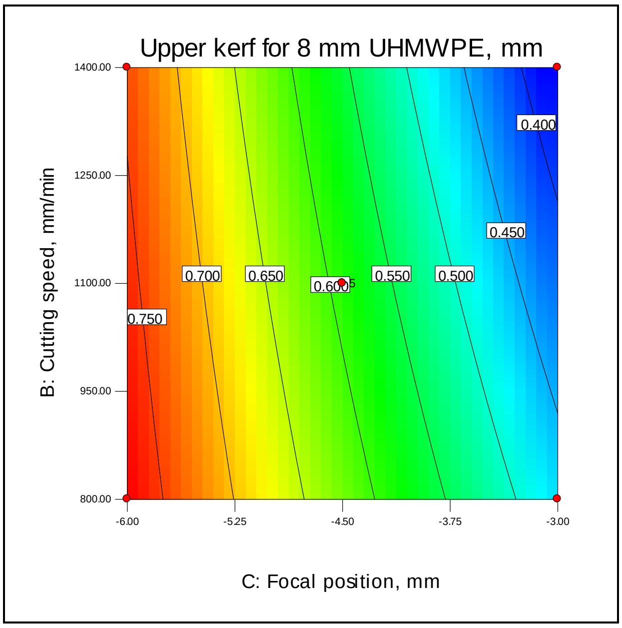



(a) (b) (c)

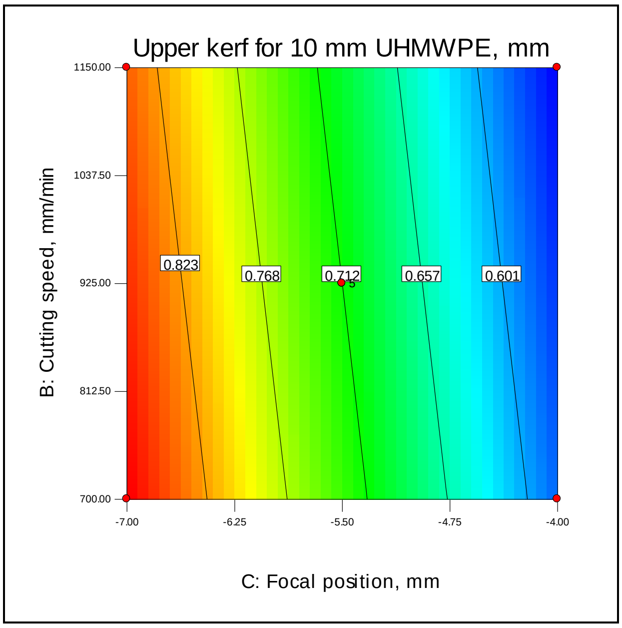
Fig. 1: Perturbation plots illustrating the effect of each factor on the upper kerf for the (a) 6 mm thick, (b) 8 mm thick and (c) 10 mm thick.




(a)

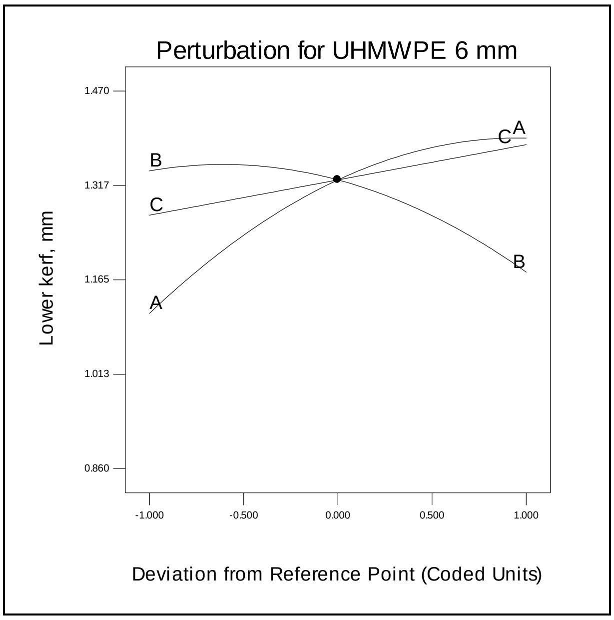



(b)

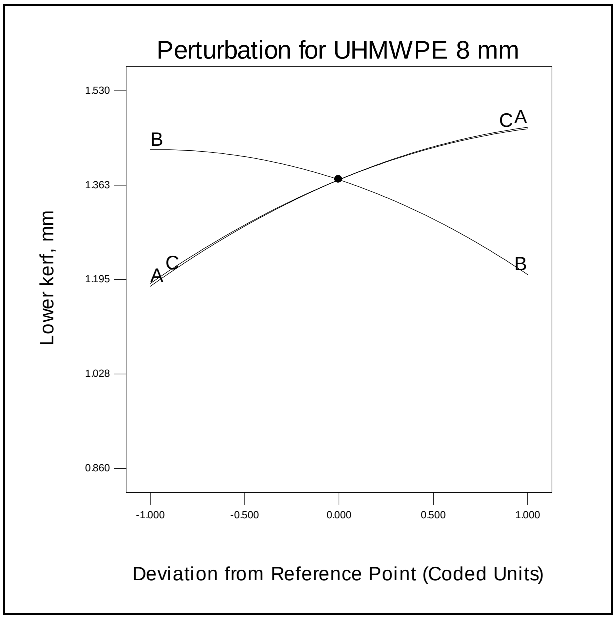



(c)

Fig. 2: Contour plots showing the effect of focal position and cutting speed on the upper kerf for the (a) 6 mm thick, (b) 8 mm thick and (c) 10 mm thick.




(a)

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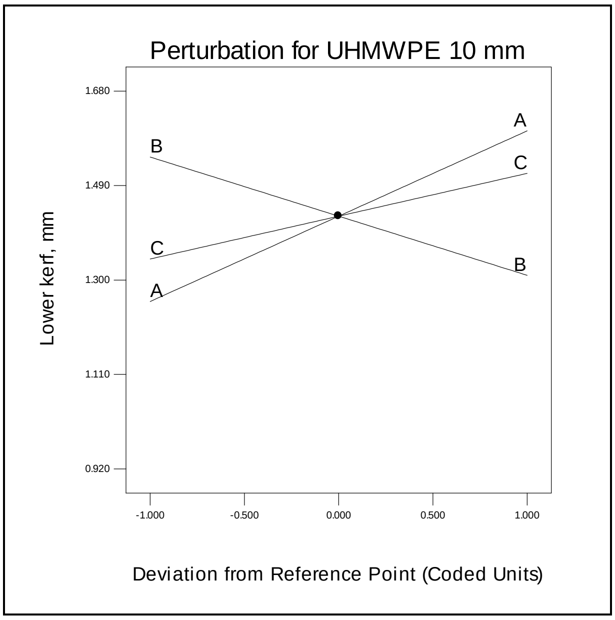
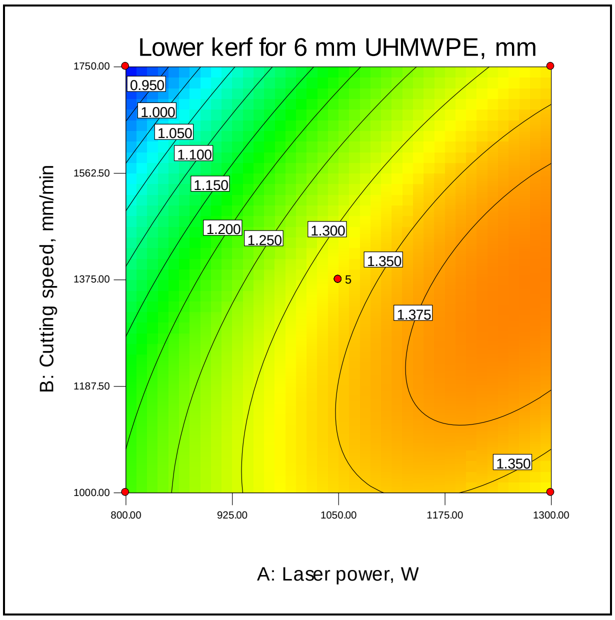
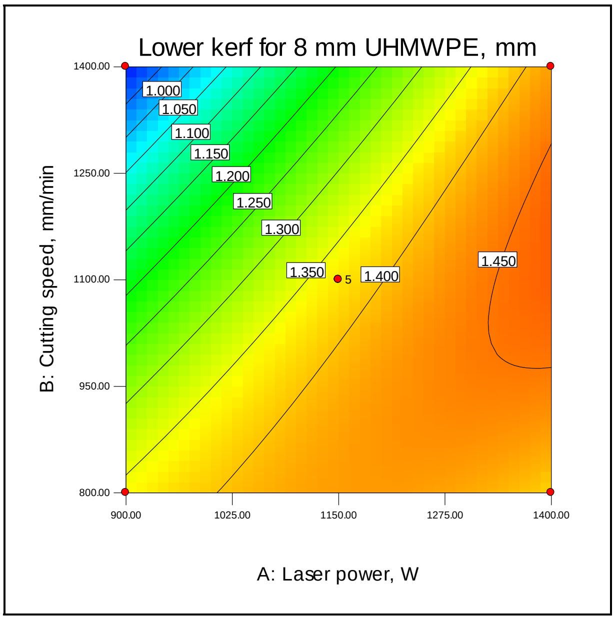



(c)

Fig. 3: Perturbation plots illustrating the effect of each factor on the lower kerf for the (a) 6 mm thick, (b) 8 mm thick and (c) 10 mm thick.




(a)

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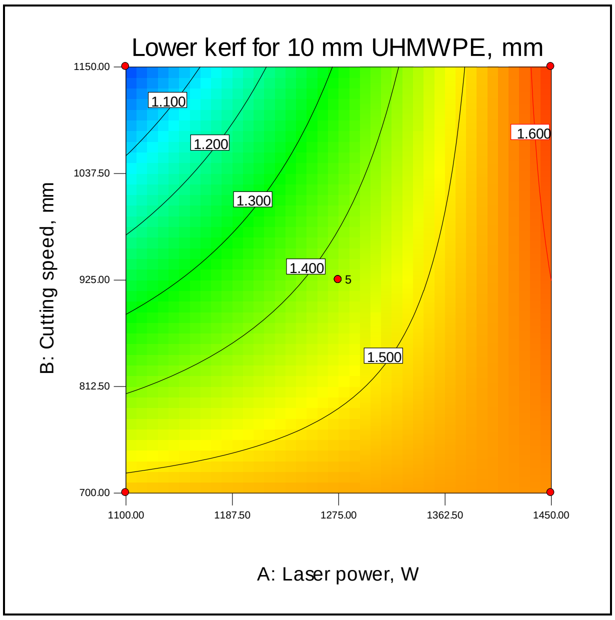
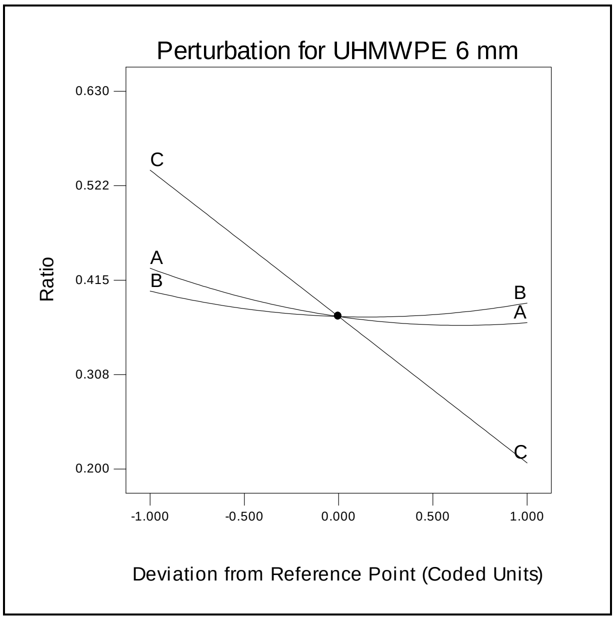



(c)

Fig. 4: Contour plots showing the effect of cutting speed and laser power on the lower kerf for the (a) 6 mm thick, (b) 8 mm thick and (c) 10 mm thick.

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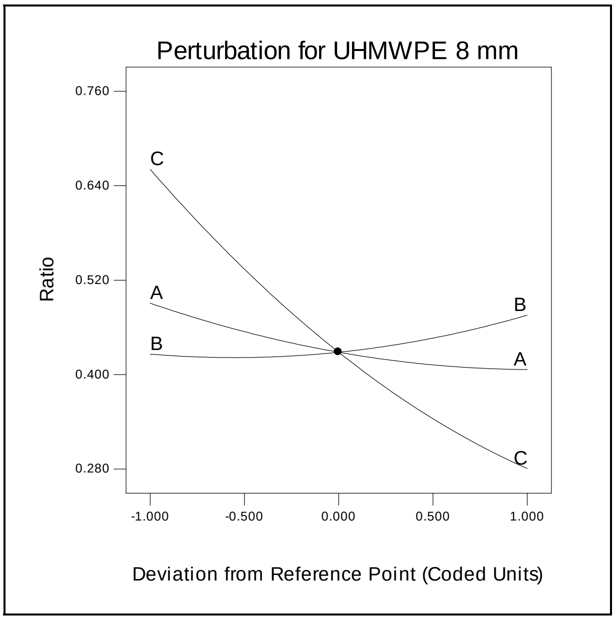


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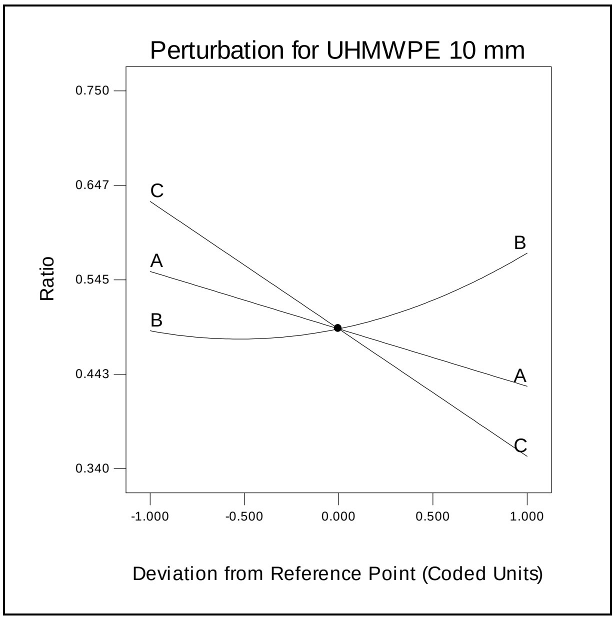
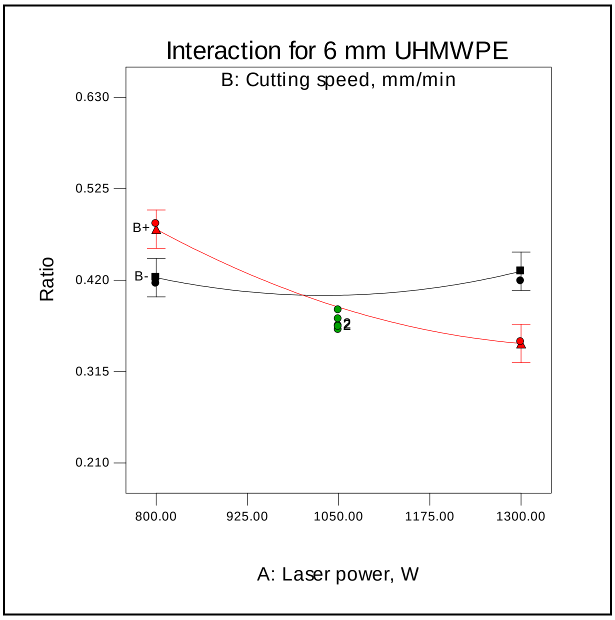



(c)

Fig. 5: Perturbation plots illustrating the effect of each factor on the ratio between kerfs for the (a) 6 mm thick, (b) 8 mm thick and (c) 10 mm thick.

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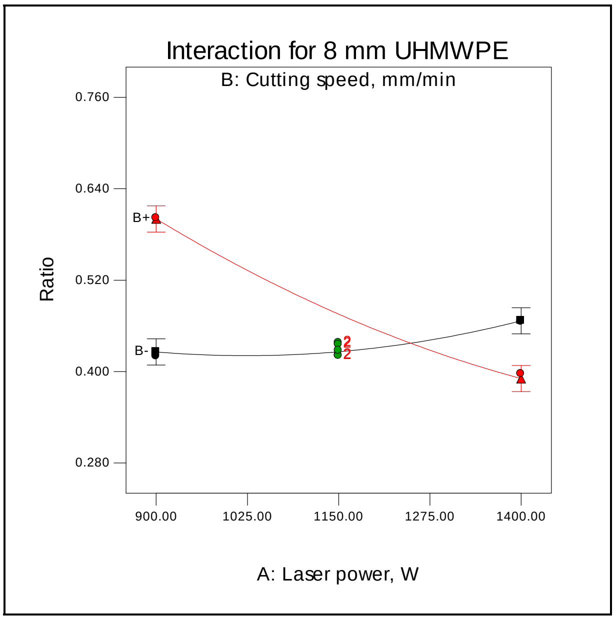


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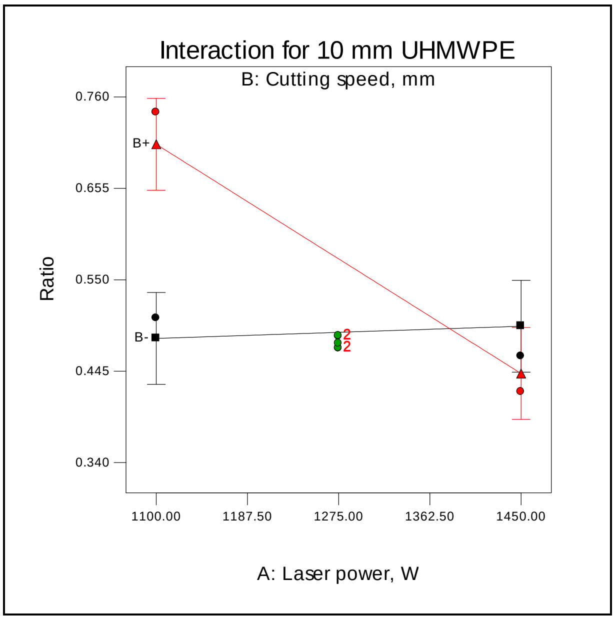
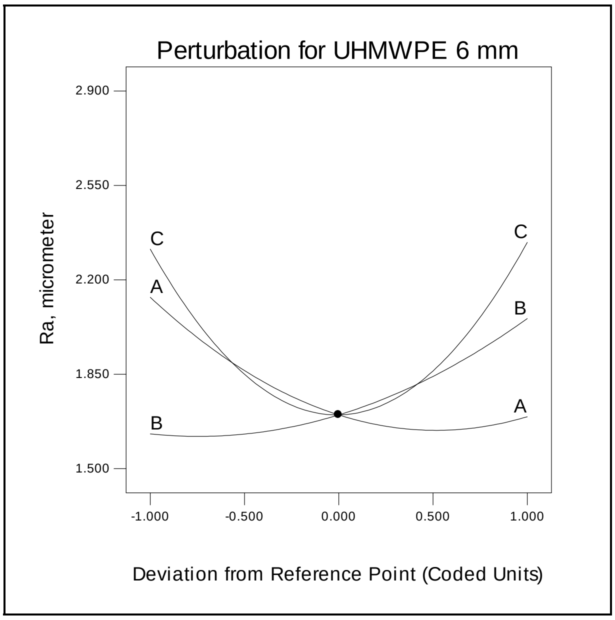



(c)

Fig. 6: Interaction graph illustrating the interaction effect between cutting speed and laser power on the ratio for the (a) 6 mm thick, (b) 8 mm thick and (c) 10 mm thick.

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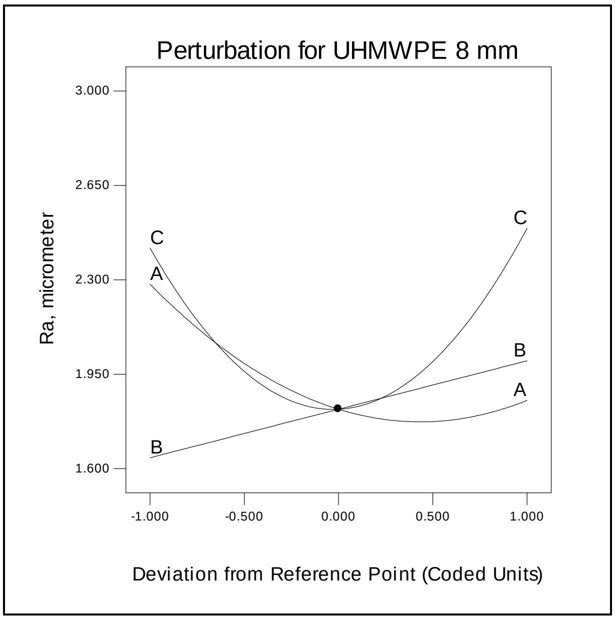


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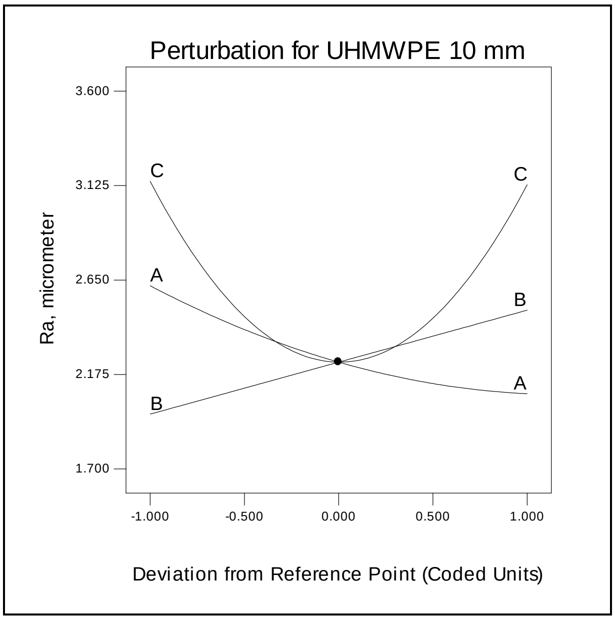
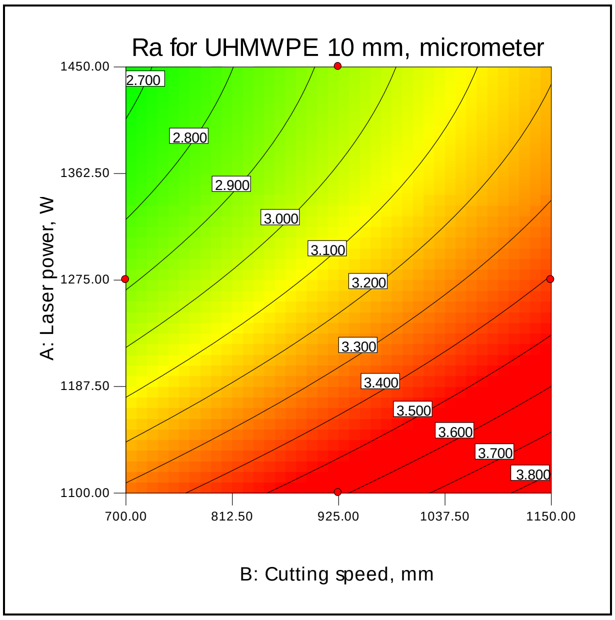
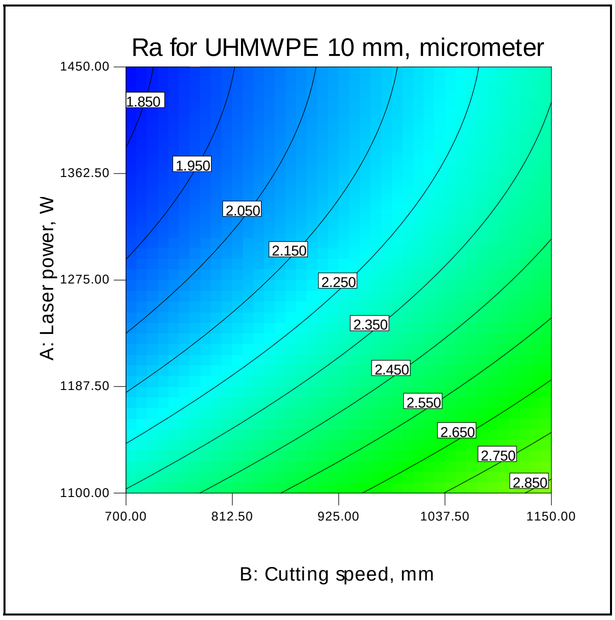



(c)

Fig. 7: Perturbation plots illustrating the effect of each factor on the roughness for (a) 6 mm thick, (b) 8 mm thick and (c) 10 mm thick.




(a)

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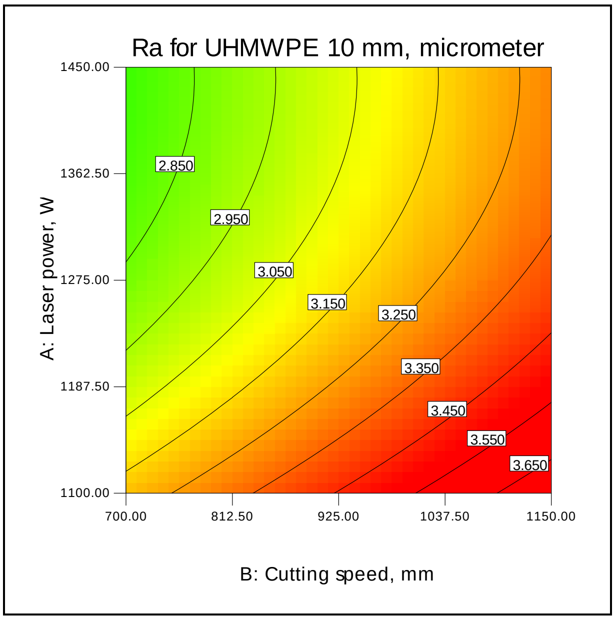


(c)

Fig. 8: Contour plots shows the effect of cutting speed and laser power on the roughness for 10 mm thick UHMWPE at three levels of focal position. (a) F = -7 mm, (b) F = -5.5 mm and (c) F = -4 mm.

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