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ORIGINAL ARTICLE

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Statistical analysis of repeatability in laser percussion drilling

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Abstract This study investigates the effect of six parameters in the repeatability of drilled holes in laser percussion drilling process by means of statistical techniques. Peak power, pulse width, pulse frequency, number of pulses, gas pressure and focal plane position were considered as independent process parameters. Experiments were designed with the aim of reducing the number of required experiments. The response surface method was used to develop the models for required responses. The significant factors in the process were selected based on the analysis of the variance (ANOVA). The experiments were conducted in mild steel sheet with a thickness of 2 mm. Each experiment was repeated 35 times in order to investigate the repeatability of the process. The equivalent entrance diameter, percentage of standard deviation of entrance diameter (%STD Eq Dia), circularity (ratio of minimum to maximum Feret's diameter) and its standard deviation (STD circularity) were selected as process characteristics. The %STD Eq Dia and STD circularity, respectively, show the repeatability of equivalent diameter and circularity in the process.

The results show that the process of drilling smaller hole diameters is more repeatable than drilling larger holes. Pulse width, gas pressure, focal plane position, peak power and number of pulses, respectively, have significant effect on the repeatability of hole diameter and circularity. Pulse frequency has no significant effect on the repeatability of the process.

Keywords Laser drilling · Repeatability · Response surface method · Statistical analysis

1 Introduction

Laser percussion drilling has been applied widely in industry. Repeatability is one of the concerns to meet tight industrial tolerances since the process does not always produce a desired hole. Laser drilling is governed by a large number of parameters; as such, the development of a physical model is very complicated.

Experimental design technique and a statistical approach can be very powerful and appropriate tools to find the significant factors in a particular process. The planned experimental design can be followed by regression techniques to model the process quantitatively. Yilbas and Yilbas [1] used a statistical approach to investigate the effects of the variation of single pulse laser drilling parameters on hole geometry. Yilbas [2] studied the effects of parameters in the single pulse laser drilling of various sheet metals by using full factorial design with five factors at four levels. Four quantitative factors (energy, focal plane position, thickness and vacuum pressure) and one qualitative factor (material specification) were used in the model to identify the effects of the main and first order interaction of factors on hole quality, which induced resolidified material, taper, barrelling, inlet cone, exit cone, surface debris and mean hole diameter. Yilbas [3] further investigated the effects of five factors at four levels (focal length of lens, pulse length, focus setting, laser energy and thickness of material) on drilling speed in the single pulse laser drilling of four different materials. French et al. [4] studied the Nd:YAG laser percussion drilling using factorial experimental design. Two level factors were used in their designs to find the significant factors from a list of 17. Main effects of the factors and first and second order interactions were analysed. They concluded that factorial design is a powerful tool in analysing laser percussion drilling where the process can be affected by a large number of parameters. Kamalu and Byrd [5] applied a statistical procedure to the design of laser percussion drilling with a Nd:YAG laser. The experiments were carried out on nickel-based alloy sheet material. Their studies were conducted to assess the effects of lens focal length, position of the focal plane relative to the material surface and laser energy on drilling performance. Tam et al. [6] optimised laser deep hole drilling in Inconel 718 by using the Taguchi method to minimise the drilling time. They used single, double and triple pulse shapes plus four factors at three levels (pulse energy, pulse duration, focal plane position and assist gas pressure) in their design.

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Ghoreishi et al. [7–9] studied the effects of the six independent factors and their effects on hole taper and hole circularity in laser percussion drilling. They carried out their experiments on mild steel and stainless steel materials.

2 Experimental method

2.1 Laser drilling procedures

Laser drilling experiments were performed on mild steel EN3 sheets with a thickness of 2 mm by means of a fibre-optic (600 μm core diameter)-delivered 400 W pulsed Nd:YAG laser emitting at a wavelngth of 1.06 μm. Oxygen was used as assist gas in the experiments. Through-holes were drilled in all experiments, and each experiment was repeated 35 times in order to analyse the repeatability of the process and also to obtain the mean value for the responses. The experiments were divided into three blocks and experiments of each block were carried out in one day. In total, all the experiments were performed in three days. Blocking is advantageous when there is a known factor that may influence the experimental result, but its effect is not of interest. In this study, blocking the experiments could eliminate the effect of laser machine performance and environmental conditions during experiments. Each block of experiments was performed randomly so that they follow no particular pattern.

2.2 Design of experiments

A face-centred central composite design (CCD) with three levels for each factor was employed to design the experiments [10, 11]. The location of the axial points in a response surface central composite design is determined by alpha value. Alpha (α) is a multiplier of the $+1$ and -1 coded levels of the independent variables in the design. If alpha is 2.37, then the star point is located at 2.37 times the $+1$ level. Setting alpha equal to 1 creates a face-centered central composite design in which each variable can be set on three levels. Another class of three level design is fractional factorial design. This type of design for six parameters at three levels has a similar structure. One-ninth of fractional factorial design is resolution III, which means two factor interactions cannot be estimated. A design of resolution III confounds main effects with two-factor interactions [11].

Therefore, face-centred CCD is the best alternative for this study. In this design, each factor has three levels of coded factors – -1, 0 and $+1$ – which represent low, medium and high levels of factors. This design requires 49 experiments plus five replications of the centre runs in order to avoid singularities during regression and in estimating pure error. In total, $54 \times 35 = 1890$ holes were drilled, and required diameters were measured by an image processing technique.

2.3 Process variables

Based on previous studies [7–9], six independent factors were selected as input parameters to investigate the repeatability of the process. The factors consist of peak power, pulse width, pulse frequency, number of pulses, gas pressure and focal plane position (FPP). The selected ranges for the factors are shown in Table 1.

Table 1. Independent process variables and their levels in face-centred CCD

Variable	Actual Levels		
Peak Power [kW]	3.5	5	6.5
Pulse Width [ms]	0.8	1.40	2
Pulse Frequency [Hz]	15	22.5	30
No of Pulses	8	14	20
Assist Gas Pressure [bar]	2	3.5	5
Focal plane position [mm]	−1	0	+1
Coded levels	−1	0	+1

Percentage of standard deviation for equivalent entrance diameter and standard deviation of circularity were considered as output or dependent parameters. For equivalent diameter, the percentage of standard deviation was considered to be able to compare the different diameter ranges for each parameter setting. Circularity is the ratio of minimum to maximum Feret's diameter for hole entrance. The Feret diameter is the distance between two tangents on opposite sides of the hole, parallel to some fixed direction [12]. Higher ratios and ratios close to one indicate holes with more circularity. Also, equivalent entrance diameter and circularity for hole entrance were considered as responses in order to compare the results with previous studies and to complete the discussion of the effect of parameters on the process. The spatter accumulated around the holes was removed using abrasive cleaner to obtain the best result during image processing. An image processing and analysis software was utilised to analyse and measure the required diametrical dimensions, which were then used as responses in this study.

3 Experimental results and data analysis

Statistical modelling was carried out to develop the mathematical models relating the four responses (outputs) to the six independent variables. The responses were established based on the response surface method and multiple regression analysis [13].

The significant parameters were found by analysis of variance (ANOVA), and then the insignificant parameters were removed from the model by a stepwise regression technique. The face-centred CCD can handle quadratic models. In all cases, modelling was started with a second order model because this includes both the interaction and the quadratic terms of independent variables. By this means, any non-linearity or curvature in the response would be considered, and if non-linearity was not appropriate, then the model was reduced to first order. The second order model η is presented as:

$$\eta = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum \sum\nolimits_{i<k} \beta_{ij} x_i x_j \qquad (1)$$

where k is the number of independent variables. In the present case, $k = 6$. The coefficient β_0 represents the response at the centre of the experiment when all of the variables are zero. β_j, β_{jj}, and β_{ij} represent the linear, quadratic and linear-by-linear interaction effects of the variables, respectively.

The regression coefficients were computed according to the least squares procedure and stepwise regression (Table 6). A complete analysis of variance was performed to test the significance of the obtained coefficients at 1% and 5% levels for highly significant and significant factors, respectively. The significant terms in each response are illustrated in Tables 2 to 5. The final models have been developed by assessing the normal probability line of residuals to check the normality assumption of residuals, assessing the outliers to check the unfitted design points, assessing Cook's distance to evaluate the effect of any particular experiment, considering leverage to assess the potential of a design point to influence the model fit, and finally a complete checking of residuals [10]. Power transformation of the responses have been selected according to the Box-Cox plots in order to minimise residual sum of squares in the transformed model [11].

As can be seen in Table 2, peak power, pulse width, gas pressure, focal plane position are highly significant and the interactions effect between peak power and gas pressure, pulse width

Table 2. ANOVA table of Equivalent entrance diameter

Source	Sum of squares	DF	Mean square	F value	Prob > F	
Block	5.429E−010	2	2.715E−010			
Model	1.661E−007	7	2.373E−008	91.99	< 0.0001	h.significant
A	2.629E−008	1	2.629E−008	101.93	< 0.0001	h.significant
B	1.157E−007	1	1.157E−007	448.52	< 0.0001	h.significant
E^2	2.021E−008	1	2.021E−008	78.35	< 0.0001	h.significant
F^2	1.062E−008	1	1.062E−008	41.19	< 0.0001	h.significant
AE	1.158E−009	1	1.158E−009	4.49	0.0398	significant
BF	1.358E−009	1	1.358E−009	5.26	0.0266	significant
EF	1.360E−009	1	1.360E−009	5.27	0.0265	significant
Residual	1.135E−008	44	2.579E−010			

A = Peak power, B = Pulse width, C = Pulse frequency, D = No of pulses, E = Gas pressure, F = Focal plane position
$\alpha = 0.01$ highly significant, $\alpha = 0.05$ significant

Table 3. ANOVA table of percentage of standard deviation (%STD) of Equivalent entrance diameter

Source	Sum of squares	DF	Mean square	F value	Prob > F	
Block	0.089	2	0.045			
Model	0.73	7	0.10	28.56	< 0.0001	h.significant
B	0.23	1	0.23	64.53	< 0.0001	h.significant
E	0.060	1	0.060	16.50	0.0002	h.significant
F	0.11	1	0.11	29.80	< 0.0001	h.significant
D^2	0.020	1	0.020	5.61	0.0223	significant
E^2	0.19	1	0.19	52.61	< 0.0001	h.significant
BE	0.033	1	0.033	9.13	0.0042	h.significant
BF	0.019	1	0.019	5.16	0.0280	significant
Residual	0.16	44	3.632E−003			

A = Peak power, B = Pulse width, C = Pulse frequency, D = No of pulses, E = Gas pressure, F = Focal plane position
$\alpha = 0.01$ highly significant, $\alpha = 0.05$ significant

Table 4. ANOVA table of circularity (Minimum/Maximum Feret's diameter)

Source	Sum of squares	DF	Mean square	F value	Prob > F	
Block	0.040	2	0.020			
Model	0.79	5	0.16	26.98	< 0.0001	h.significant
B	0.33	1	0.33	55.97	< 0.0001	h.significant
E	0.15	1	0.15	24.73	< 0.0001	h.significant
E^2	0.20	1	0.20	34.84	< 0.0001	h.significant
AE	0.075	1	0.075	12.79	0.0008	h.significant
EF	0.039	1	0.039	6.58	0.0137	significant
Residual	0.27	46	5.872E−003			

A = Peak power, B = Pulse width, C = Pulse frequency, D = No of pulses, E = Gas pressure, F = Focal plane position
$\alpha = 0.01$ highly significant, $\alpha = 0.05$ significant

Table 5. ANOVA table of standard deviation of circularity

Source	Sum of squares	DF	Mean square	F value	Prob > F	
Block	0.79	2	0.39			
Model	9.40	7	1.34	27.68	< 0.0001	h.significant
A	0.38	1	0.38	7.83	0.0076	h.significant
B	2.42	1	2.42	49.89	< 0.0001	h.significant
E	2.60	1	2.60	53.55	< 0.0001	h.significant
E^2	2.66	1	2.66	54.88	< 0.0001	h.significant
BE	0.29	1	0.29	5.95	0.0188	significant
BF	0.80	1	0.80	16.45	0.0002	h.significant
DE	0.25	1	0.25	5.22	0.0272	significant
Residual	2.13	44	0.048			

A = Peak power, B = Pulse width, C = Pulse frequency, D = No of pulses, E = Gas pressure, F = Focal plane position
$\alpha = 0.01$ highly significant, $\alpha = 0.05$ significant

Table 6. Final models of four responses in terms of significant factors (in coded form)

Coefficient	Model			
	$(\text{Ent. Dia})^{-1.14}$ $[\text{micron}]^{-1.14}$	$(\%\text{STD Eq Dia})^{-0.52}$	$(\text{Circularity})^3$	Ln(STD Circularity)
β_0	+3.731E−004	+0.41	+0.46	−2.64
β_A	−2.781E−005	insignificant	insignificant	−0.11
β_B	−5.833E−005	−0.083	−0.098	+0.27
β_E	insignificant	−0.042	−0.065	+0.28
β_F	insignificant	+0.056	insignificant	insignificant
β_D^2	insignificant	−0.076	insignificant	insignificant
β_E^2	+7.591E−005	+0.23	+0.16	−0.57
β_F^2	−5.503E−005	insignificant	insignificant	insignificant
$\beta_{A\times E}$	−6.016E−006	insignificant	−0.048	insignificant
$\beta_{B\times E}$		−0.032	insignificant	+0.095
$\beta_{B\times F}$	+6.513E−006	+0.024	insignificant	−0.16
$\beta_{D\times E}$		insignificant	insignificant	+0.089
$\beta_{E\times F}$	−6.518E−006	insignificant	+0.035	insignificant

Models of repeatability in laser percussion drilling in terms of coded factors:
A = Peak power, B = Pulse width, C = Pulse frequency, D = No of pulses, E = Gas pressure, F = Focal plane position

and focal plane position, and gas pressure and focal plane position are significant.

From Table 3, it can be seen that pulse width, gas pressure, focal plane position are highly significant, and number of pulses (quadratic term) is significant. Also, interaction between pulse width and gas pressure is highly significant, and interaction between pulse width and focal plane position is significant. It should be mentioned that the results of the analysis can be used qualitatively; this leads to the establishment of some guidelines to make the process as repeatable as possible. This can be achieved by statistical analysis of the process.

Table 4 indicates that the model is highly significant, and pulse width, gas pressure (linear and quadratic terms) are also highly significant. The interaction between peak power with gas pressure is highly significant, while the interaction between gas pressure with focal plane position has a significant effect on the process. The ANOVA result of standard deviation of circularity is shown in Table 5.

Peak power, pulse width and gas pressure (linear and quadratic terms) a have highly significant effect on the STD of circularity or repeatability of hole circularity. Interaction between pulse width and focal plane position is highly significant, while interactions between pulse width and gas pressure, and the number of pulses and gas pressure are significant.

The final models of four responses – Eq Dia, %STD Eq Dia, Circularity and STD Circularity have been computed based on stepwise regression technique, and are shown in Table 6.

Table 7. Summarised table of significant factors and interactions on the repeatability responses

Factor	Response	
	%STD Ent Dia	STD Circilarity
A	insignificant	h.sig
B	h.sig	h.sig
C	insignificant	insignificant
D	sig	insignificant
E	h.sig	h.sig
F	h.sig	insignificant
B × E	h.sig	sig
B × F	sig	h.sig
D × E	insignificant	sig

A = Peak power, B = Pulse width, C = Pulse frequency, D = No of pulses, E = Gas pressure, F = Focal plane position
h.sig = highly significant ($\alpha = 0.01$) sig = significant ($\alpha = 0.05$)

4 Discussion

4.1 Equivalent entrance diameter

Peak power, pulse width, gas pressure and focal plane position have a significant effect on this response. Also, interactions of peak power with gas pressure, pulse width with focal plane position, and gas pressure with focal plane position are significant. The perturbation curves of main effect of the parameters is shown in Fig. 1, and the interaction curves are shown in Fig. 2a–c. It should be noted that the interaction effects are only significant when the main effects of the parameters are highly significant. Thus, in interaction curves not much of a difference can be seen between the trend of responses' variation. In summary, it can be concluded that a shorter pulse width and lower peak power generate a smaller hole diameter. Pulse frequency and number of pulses have no significant effect on the

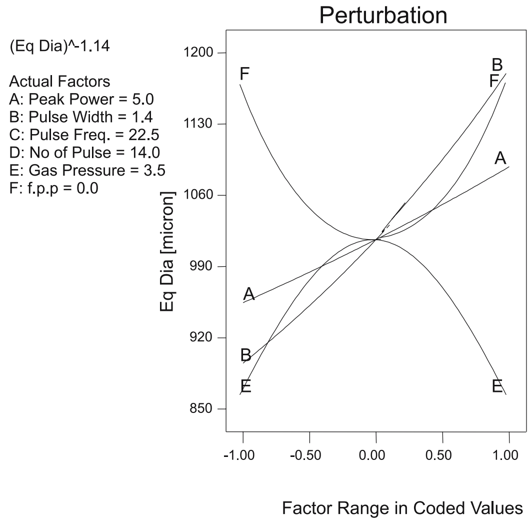

Fig. 1. Main effect of the parameters on Eq. Dia response

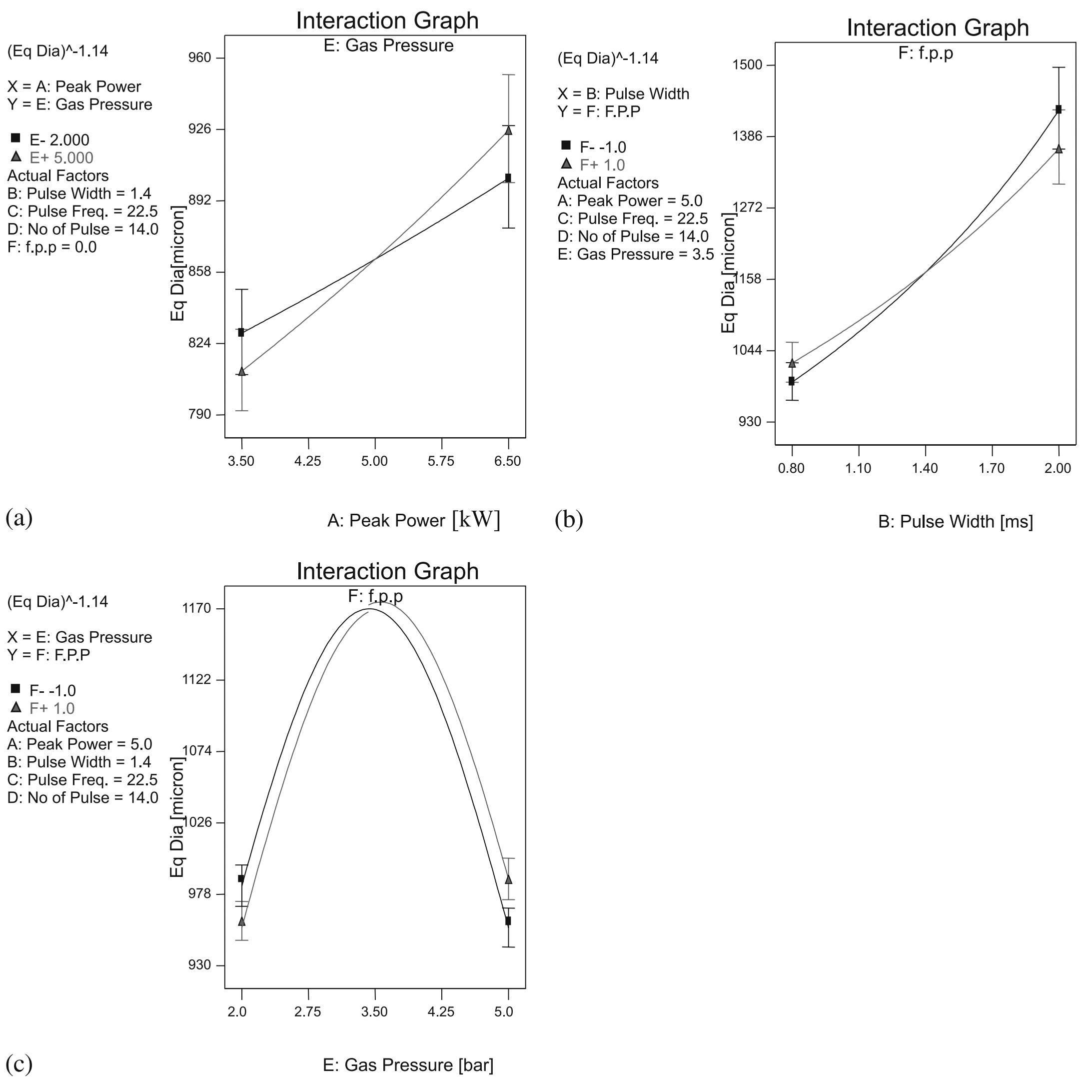

Fig. 2a–c. Interaction effect between **a** peak power and gas pressure on Eq Dia, **b** pulse width and FPP on Eq. Dia, and **c** gas pressure and FPP on Eq. Dia

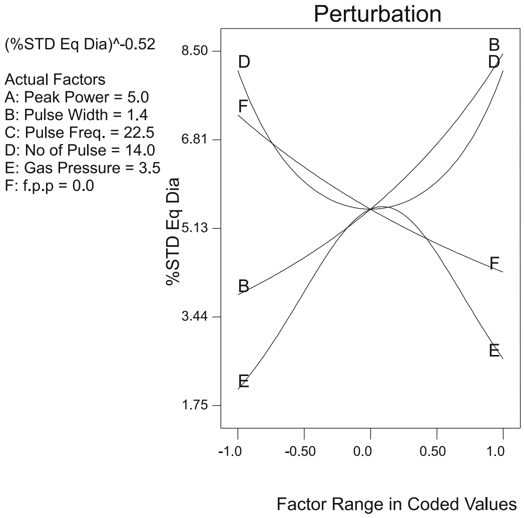

Fig. 3. Main effect of the parameters on "%STD Eq. Dia" response

hole diameter. This result is in agreement with the previous results [7].

4.2 Percentage of standard deviation of Eq Dia (%STD Eq Dia)

Pulse width, gas pressure, FPP and interaction between pulse width and gas pressure have a highly significant effect on this response. The number of pulses and the interaction between pulse width and FPP a have significant effect. In this case, just like Eq Dia, the pulse frequency has no significant effect on the repeatability of hole diameter, but the number of pulses has a significant effect on the diameter repeatability. The perturbation and interaction curves are shown in Figs. 3 and 4a and b, respectively.

Here, lower values of the response are desirable. From Fig. 3, it can be seen that working with a shorter pulse width and a positive FPP makes the process more repeatable. Also, with regards to Fig. 4a, working at a lower gas pressure improves the repeatability of the process. Figure 4b reveals that working at a positive FPP and lower pulse width is desirable and produces more repeatability.

In summary, it can be concluded that a positive FPP with a shorter pulse width, a lower gas pressure and a moderate number of pulses make the process more repeatable. Compared to the findings for Eq Dia, it can be concluded that in drilling smaller hole diameters, the process is much more repeatable than drilling larger hole diameters.

It should be noted that variation of peak power within the considered range (3.5 to 6.5 KW) has no significant effect on the diameter repeatability. Choosing a wider range for peak power would more likely make it a significant parameter. However, peak power has a highly significant effect on the hole diameter even within the considered range of variation.

4.3 Circularity (Min/Max Feret's entrance diameter)

The ratio of minimum to maximum Feret's diameter represents the circularity at the entrance diameter. For this response, pulse width, gas pressure and the interaction between peak power and gas pressure have a highly significant effect, while the interaction between gas pressure and FPP has a significant effect on the circularity. In this case, just like for Eq Dia, pulse frequency and number of pulses have no significant effect on the response. The main effect of the parameter on the circularity is shown in Fig. 5 in a perturbation curve.

It can be seen that a lower gas pressure and shorter pulse width produces more circular holes, while FPP and peak power have no significant effect on the circularity, but they do have significant effect in interactions. The interaction curves are shown in Fig. 6(a and b).

From Fig. 6a, it can be seen that working with a lower gas pressure and a higher peak power produces more circular holes. Working with a lower gas pressure and a negative FPP can im-

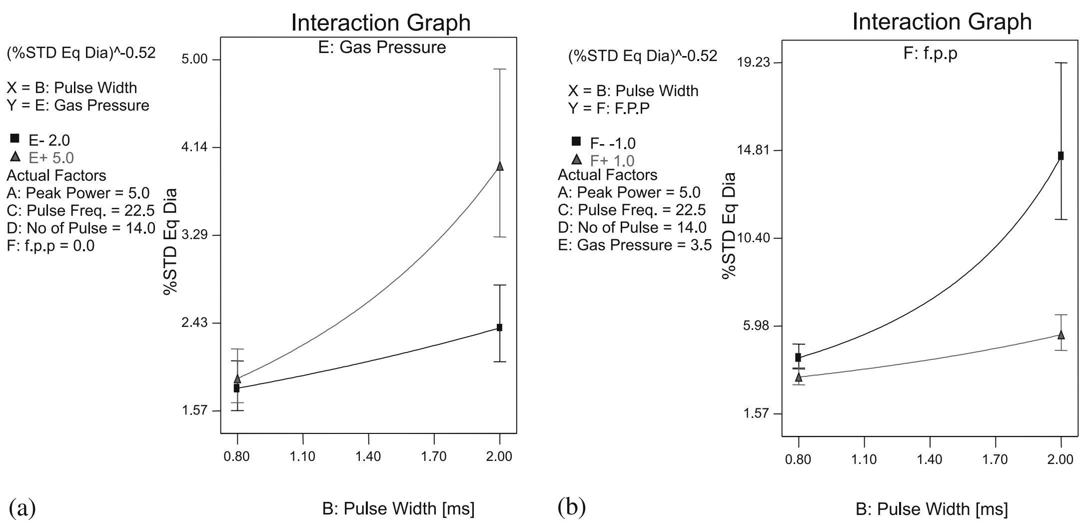

Fig. 4a,b. Interaction effect between **a** gas pressure and pulse width on %STD Eq Dia, and **b** FPP and pulse width on %STD Eq Dia

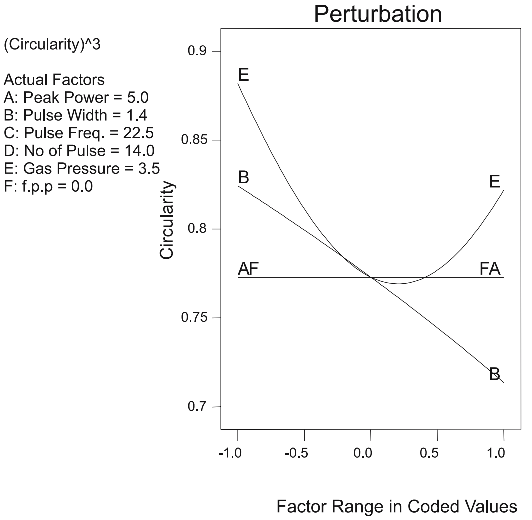

Fig. 5. Main effect of the parameters on circularity response

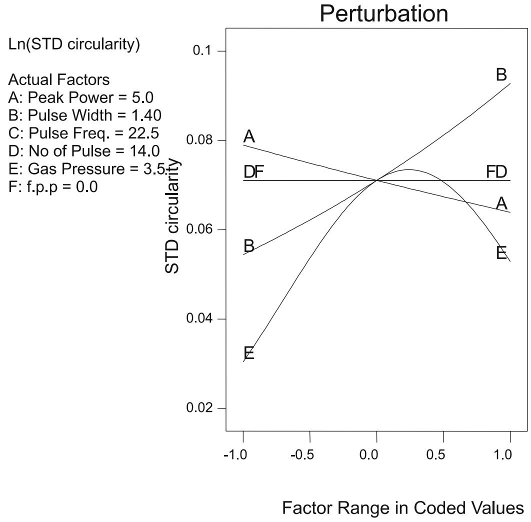

Fig. 7. Main effect of the parameters on STD circularity response

prove hole circularity (Fig. 6b). However, the effect of this interaction is only significant and variation of FPP from positive to negative does not cause much of a difference in hole circularity (0.86 to 0.90).

In summary, shorter pulse width, higher peak power, lower gas pressure, and negative FPP improve hole circularity. Pulse frequency and number of pulses have no significant effect on hole circularity.

4.4 Standard deviation of circularity (STD Circularity)

Here, peak power, pulse width, gas pressure and the interaction between pulse width and FPP have a highly significant effect on the response, while the interaction between pulse width and gas pressure, and gas pressure and the number of pulses, have a significant effect on the STD Circularity. The main effect of the parameters is shown in Fig. 7. For this response, lower values are desirable. From Fig. 7, the variation of the circularity for repeated holes is smaller. Thus, shorter pulse width, lower gas pressure and higher peak power produce holes with more repeated circularity, while the FPP and number of pulses have no significant effect on the response, but their interactions have significant effect. For this response, just like in the other responses, pulse frequency has no significant effect.

The interaction curves are shown in Fig. 8(a, b and c). From Fig. 8a, it can be seen that a shorter pulse width working at a negative FPP is desirable and reduces STD circularity.

Figure 8b confirms the previous result regarding working at a lower gas pressure and shorter pulse width. From Fig. 8c, it can be seen that working at a lower gas pressure and with a larger number of pulses, STD circularity is reduced, which is desirable.

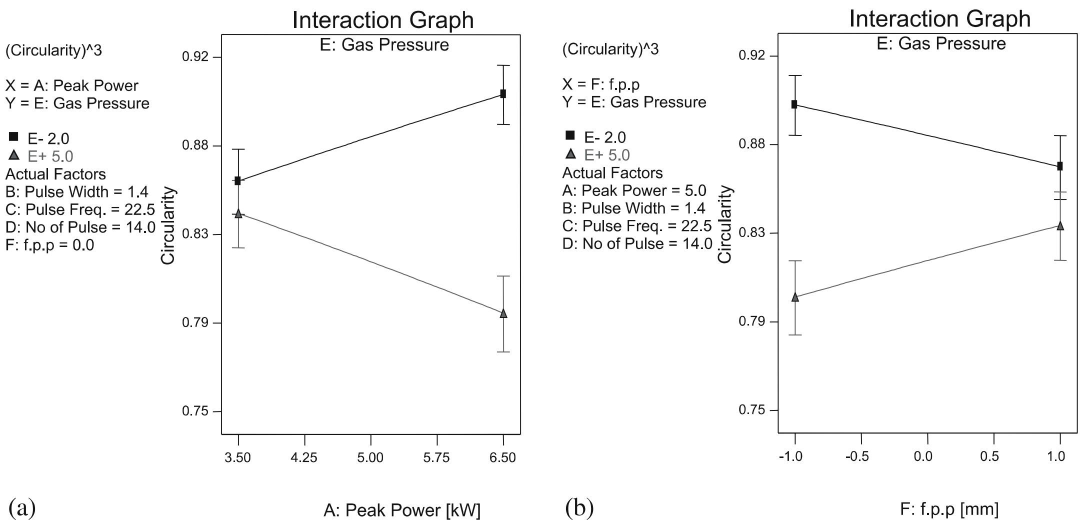

Fig. 6a,b. Interaction effect between **a** peak power and gas pressure on circularity, and **b** FPP and gas pressure on circularity

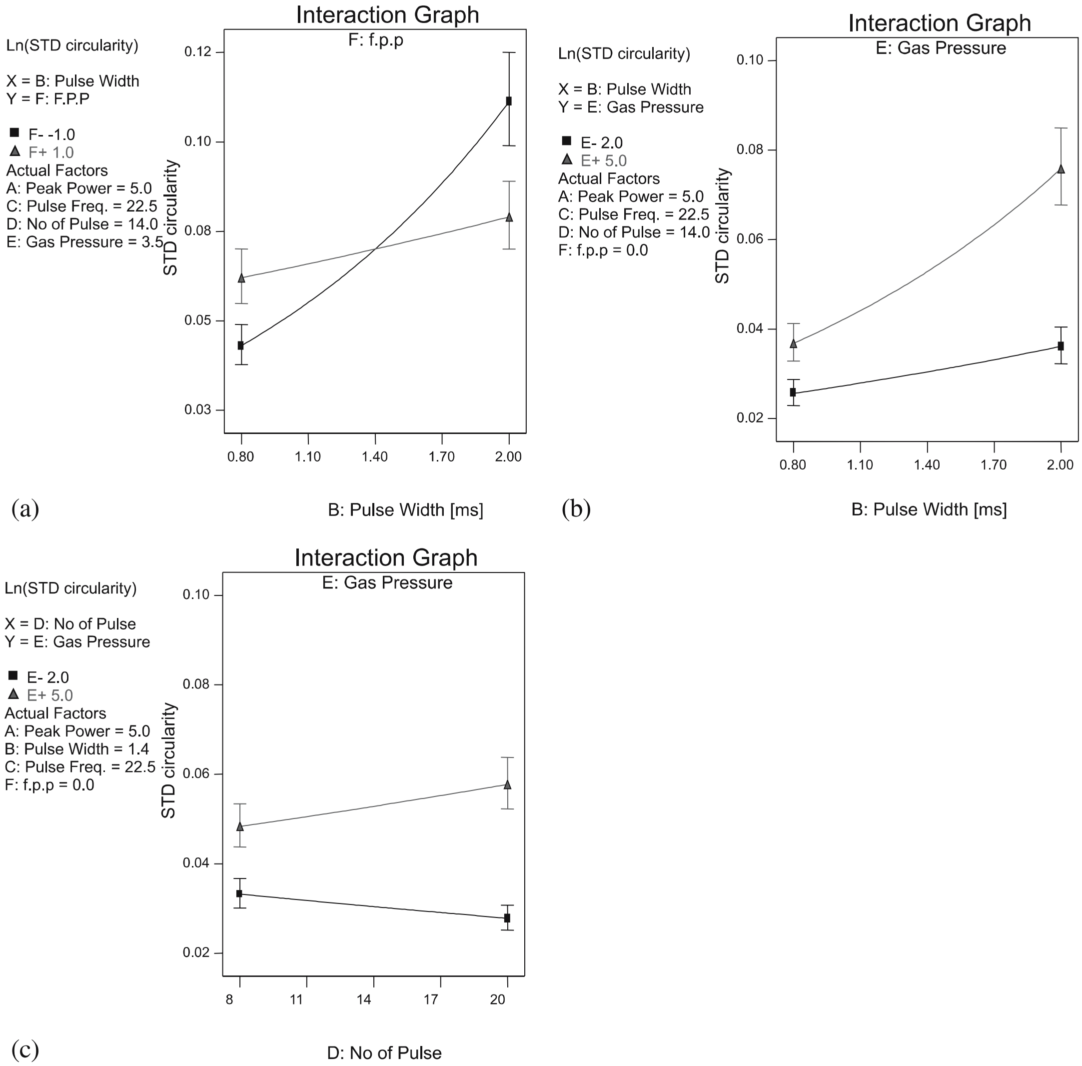

Fig. 8a–c. Interaction effect between **a** FPP and pulse width on STD circularity, **b** gas pressure and pulse width on STD circularity, and **c** gas pressure and number of pulses on STD circularity

If the result for this response is compared to the Circularity response, it can be concluded that working with shorter pulse width, higher peak power, lower gas pressure, and higher number of pulses at a negative focal plane position produces hole with greater circularity and improves repeatability of the hole circularity. Thus, for circularity, it smaller holes are more repeatable because higher peak power produces larger hole diameters. Therefore, smaller holes can be drilled by laser percussion drilling process with more repeatability when the only target is hole diameter. However, if the hole circularity is added to the list of targets, then a compromise should be made between repeatability of hole diameter and repeatability of hole circularity.

5 Conclusions

The following provides a summary of parameter effects on the two repeatability responses.

- In general, it can be observed that pulse width is the most significant factor – by itself and also in its interaction with other variables. It has significant effects on all four responses, and particularly on the repeatability responses. After pulse width, gas pressure, focal plane position, and number of pulses have significant effects on the repeatability of the process, with respect to hole diameter and circularity. Pulse frequency has no significant effect on the repeatability of the process, the equivalent diameter or hole circularity.
- Shorter pulse width and lower peak power generates smaller hole diameters. Pulse frequency and number of pulses have no significant effect on the hole diameter. Working at positive FPP with a shorter pulse width, lower gas pressure and a moderate number of pulses produces a more repeatable diameter. Therefore, in drilling smaller hole diameters, the process is much more repeatable than in drilling larger holes.
- Shorter pulse width, higher peak power, lower gas pressure, and negative FPP improve hole circularity. Pulse frequency

and number of pulses have no significant effects on hole circularity. Working with shorter pulse width, higher peak power, lower gas pressure, and a higher number of pulses at a negative focal plane position improve the repeatability of hole circularity. Thus, for circularity, smaller holes do not have a more repeatable circularity because higher peak power produces larger hole diameters.

- Smaller holes can be drilled by the laser percussion drilling process with more repeatability when the only target is hole diameter. However, if hole circularity is added to the list of targets, then a compromise should be made between the repeatability of hole diameter and the repeatability of hole circularity.

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