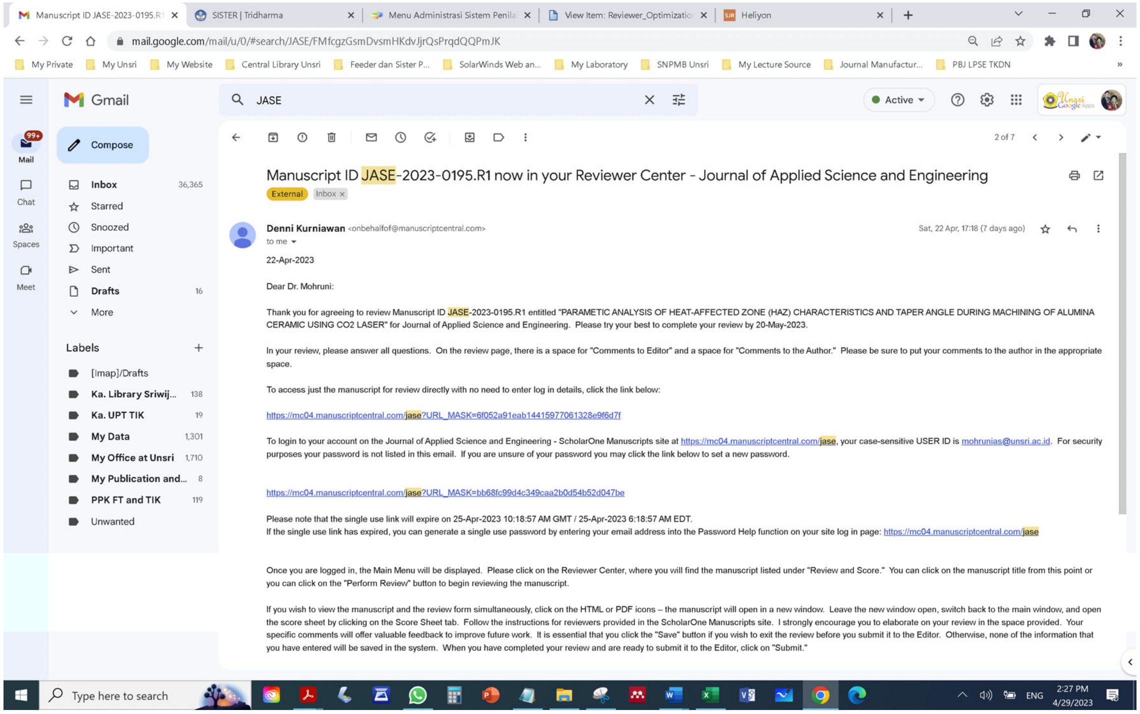

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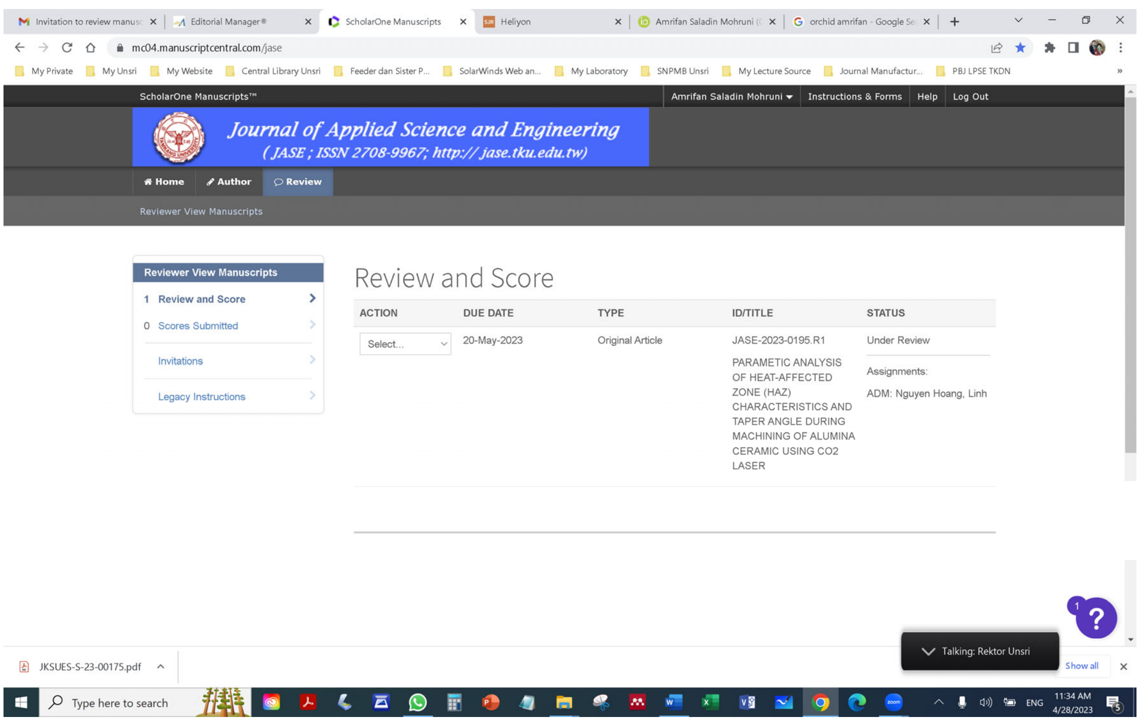

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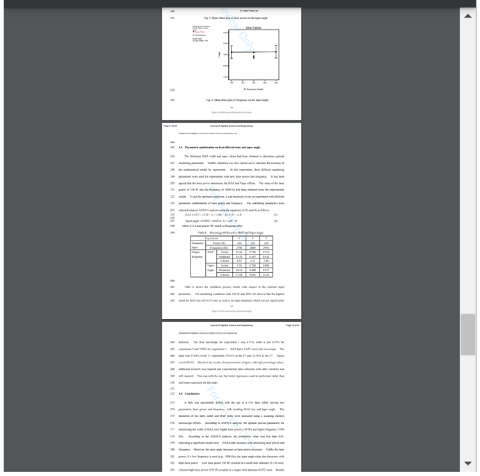

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PARAMETRIC ANALYSIS OF HEAT-AFFECTED ZONE (HAZ) CHARACTERISTICS AND TAPER ANGLE DURING MACHINING OF ALUMINA CERAMIC USING CO2 LASER

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Keywords:	Alumina, CO2 Laser machining, HAZ, Taper, Optimization

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PARAMETIC ANALYSIS OF HEAT-AFFECTED ZONE (HAZ) CHARACTERISTICS AND TAPER ANGLE DURING MACHINING OF ALUMINA CERAMIC USING CO_2 LASER

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Abstract

Alumina is widely used in the automotive, electrical component and aircraft industries due to its low thermal conductivity and high hardness. However, alumina is notoriously difficult to machine due to its extreme hardness. According to some researchers, laser machining offers a cost-effective machining technique for alumina. Even though many works on laser machining of alumina have been published, most have focused on thin alumina plates. This study determined the effect of a CO_2 laser machining method on hole quality in terms of the heat-affected zone (HAZ) and taper angle for 3 mm alumina thickness.

Design of Experiment (DOE) was performed to identify the effect of laser power, duty cycle and frequency on the output findings. The HAZ and the taper angle were measured using a Scanning Electron Microscopy image. Based on the ANOVA analysis, HAZ and taper angles were influenced by the laser power input. The HAZ thickness increased as laser power and frequency decreased, but the taper angle decreased as frequency decreased. Low laser power (50 W) resulted in a small inlet diameter (0.236 mm), while high laser power (150 W) resulted in a larger inlet diameter (0.272 mm). Multi-response optimization analysis for both HAZ and taper angle showed that 149 W and 2956 Hz frequency were the optimum process parameters which yielded the best output conditions

Keywords: Alumina; CO_2 Laser machining; HAZ; Taper; Optimization

1. Introduction

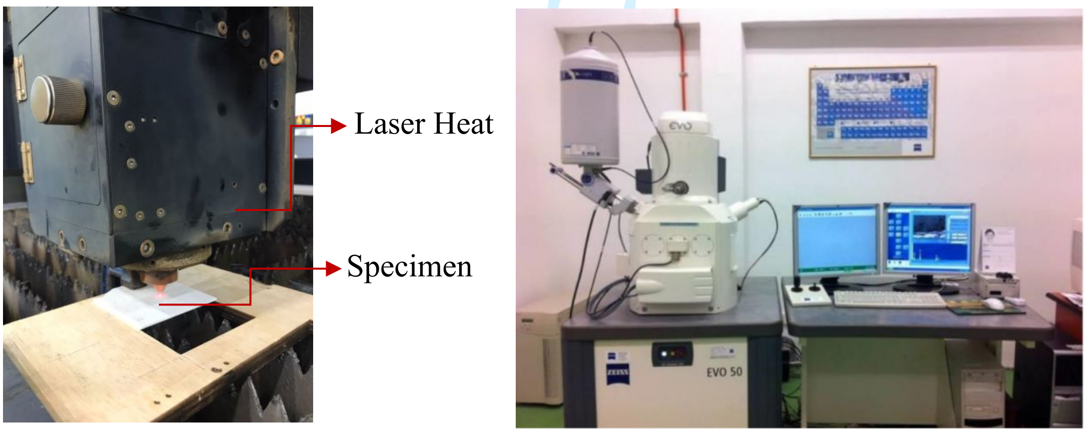
Ceramic alumina is a material which is resistant to heat and corrosion and has good electrical and chemical stability [1][2]. Ceramic alumina is widely used in the automotive, aircraft and electronics industries because of its toughness and low thermal conductivity [3][4]. This material is however difficult to manufacture due to its brittleness. The inherent brittle and high hardness of sintered ceramics, the machining of ceramic bulk material into desirable micro-components or surfaces with changing functional amounts presents numerous difficulties [5] . The most common method for working with alumina is abrasive machining. The initiative has been driven by industry requirements, particularly product specifications that call for the use of unyielding and brittle materials. [6]. However the low material removal rate (MRR) and high tool wear make conventional machining of hard ceramic materials difficult and prohibitively expensive [7]. One of the best methods to machine alumina is an ablation method such as laser machining because Laser ablation mechanism, the process of removing the surface layer from solid materials by irradiating them with laser light, has been effectively implemented, with the required temperature for the ablation process will be above 3000 K [8] [9]. High dimensional accuracy, high productivity and minimal waste are some advantages of laser machining[10][11].

HAZ and taper angle are two of the quality characteristics of laser drilling. Generally, small size for HAZ and a slight taper angle are preferred. Some studies have suggested that using high voltage during laser machining of alumina results in poorly drilled holes[12] [13]. The microstructure of the HAZ is typically made up of a microstructural granular zone and a partial melting zone [14]. The critical temperature, which is 1025^{o}C for alumina, determines the width of the HAZ, and this temperature is strongly influenced by peak pulse power settings [15] . Furthermore At large lamp current, the response surface plot indicates that the relationship between assisted gas and HAZ thickness is nearly linear. Low assisted gas is incapable of compensating for the additional heat generated at the drilling zone and is unable to aid in the removal of discharged material. Consequently, the HAZ thickness increases [16]. It has also been reported that the taper angle decreased at lower currents as the pulse frequency increased. Continued research the results indicated that as the cavity depth increased, the average taper angles decreased while the scanning speed remained constant. As scanning speed decreased, the analogous tendency of taper angles decreased at the same hole depth [17]. However, the taper angle increased at higher currents due to the high removal rate at the entrance of the hole [18]. Although the Haz and taper treatment is primarily produced by the frequency and laser power settings, the extent to which the technique applies still needs to be explored and optimized.

Most alumina laser drilling research has been conducted on thin alumina plates of less than 1 mm thickness. Thicker alumina plates have received little research attention. This study focuses on the drilling of a 3 mm alumina workpiece with a CO2 laser machine to address this gap.

2. Experimental setup

The power and frequency of the laser drilling process were the variables examined in this study. Figure 1 shows equipment setup, measurement, and workpiece installation, whereas Figure 2 illustrates the experimental process flowchart . The experiment was carried out using a full-factorial DOE technique. Design Expert software (version 10) was used to create the experimental matrix and analyze the data. The laser machining process parameters evaluated were laser power and frequency. The associated experimental matrix was tabulated as in Table 1. During the experiment, four factorial points and three centre points were assessed. The centre points were replicated three times to estimate the process variability. The output responses to be measured were the HAZ and the taper angle of the drilled holes. ANOVA and regression analysis were used to determine the significant factor influencing the output responses, the main effect and the interaction effect. A polynomial mathematical model was also developed to represent the behaviours of the HAZ and the taper angle with respect to changes in laser power and frequency.



a. Laser Machining Experiment b. SEM for HAZ and Taper

Fig.1 Setup Experiment and measurement

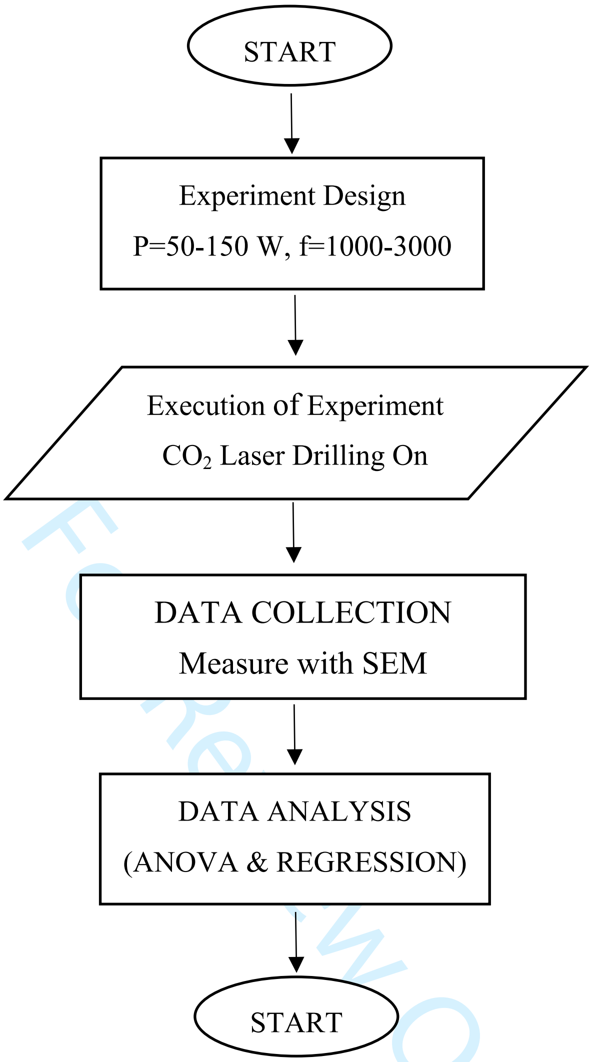


Figure 2. Process Flow Chart

Table 1. The design of the parametric experimental combination

Run	**Laser power (W)**	**Frequency (Hz)**
1	50	3000
2	50	1000
3	100	2000
4	100	2000
5	150	3000
6	100	2000
7	150	1000

The CO_2 laser system (Mitsubishi MHL2512HV2-R PLUS) was utilized in this study.

The fixed laser parameters throughout the experiment were as shown in Table 2. The workpiece material was alumina plate (Al_2O_3) with a purity of 99.7% and with dimensions of 80mm x 80mm x 3mm.

Table 2. The fixed parametric values

Fixer Parameters	**Value**
Gas pressure (Bar)	2
Piercing Time (s)	1
Duty cycle (%)	20

The images of the entrance and exit holes were observed using Scanning Electron Microscopy (SEM) model Zeiss EVO 50 with setting magnification , EHT=5.00 kV, Signal A=SE1 to determine the size of HAZ and taper angle. The width of HAZ was calculated using Equation 1 based on the SEM images. The taper angle was determined using Equation 2 [16], where D_ent is the entrance diameter, D_ext is the exit diameter of the drilled holes and *t* is the thickness of the alumina plate.

$$\text{HAZ} = \frac{\text{HAZ circle diameter} - \text{Entry Hole Diameter}}{2} \quad (1)$$

$$\text{Taper Angle } (\theta) = \tan^{-1}\frac{\text{D\_ent} - \text{D\_ext}}{2\text{t}} \quad (2)$$

Using SEM, each specimen was subjected to measurements, with measurement calculations derived from equations 1 and 2. For HAZ measurements, it was performed twice by measuring the diameter of the hole affected by the heat by the laser drilling, referred to as the *HAZ circle diameter*, and the inner diameter of the hole, referred to as the *entry hole diameter*, which is the diameter of the top surface, while the taper is measured at each entry diameter (*D_ent*) and outer diameter (*D_ext*) of the specimen. If the drilled hole is irregular in shape, the maximum diameter of the hole will be chosen as the *D_ent* or *D_ext.* Figure 3 shows the measurement scheme as follows:

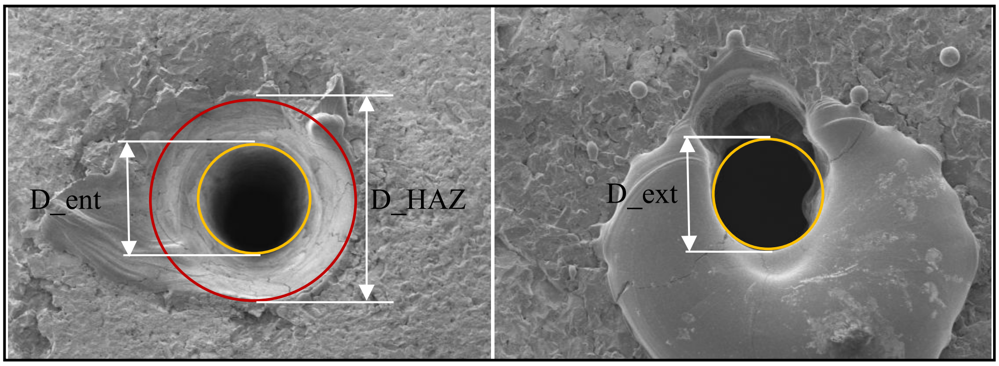


Figure 3. Schematic measuring of Haz and Taper angle

3. Result and discussions

The experimental output response on HAZ and taper angle measurement data have been tabulated in Table 3.

Table 3. Experimental output response

Run	Input Variables		Output Variables	
	Laser power (W)	Frequency (Hz)	HAZ (mm)	Taper Angle (Degree)
1	50	3000	0.176	2.253
2	50	1000	0.362	2.244
3	100	2000	0.240	1.211
4	100	2000	0.183	0.725
5	150	3000	0.145	0.762
6	100	2000	0.208	0.873
7	150	1000	0.191	0.707

3.1 Effects of Laser Power (A) and Frequency (B) on heat-affected zone

The ANOVA table generated in Table 4 shows the statistical input analysis for HAZ. Values of "Prob > F" less than 0.0500 indicated that model terms were significant. The Model Prob>F of 0.0231 implied that the model was significant. In this case, inputs A (Laser Power) and B (Frequency) were significant model terms with theProb>F values of 0.0249 and 0.0171, respectively. The "Lack of Fit F-value" of 0.14 implied that the Lack of

Fit was not significant relative to the pure error. There was a 74.42% chance that a "Lack of Fit F-value" this large could occur due to noise. The " Pred R-Squared" of 0.7829 was in reasonable agreement with the "Adj R-Squared" of 0.8847, i.e. the difference was less than 0.2 "Adeq Precision" when measuring the signal-to-noise ratio. The ANOVA analysis also showed that the interaction between laser power and frequency with the available probability values was marginally significant with Prob>F value of 0.0625.

Table 4. ANOVA statistical analysis for HAZ response

Source	Sum of square	df	Mean Square	F Value	Prob>F	
Model	0.029	3	$9.519E^{-3}$	16.35	0.0231	Significant
A	0.010	1	0.010	17.52	0.0249	Significant
B	0.013	1	0.013	23.11	0.0171	Significant
AB	$4.9E^{-3}$	1	$4.9E^{-3}$	8.41	0.0625	Not Significant
Residual	$1.747E^{-3}$	3	$5.823E^{-4}$			
Lack Of Fit	$1.143E^{-4}$	1	$1.143E^{-4}$	0.14	0.7442	Not Significant
Pure Error	$1.633E^{-3}$	2	$8.163E^{-4}$			
Cor Total	0.030	6				

Std. Dev	0.024	R-squared	0.9424
Mean	0.22	Adj R-Squared	0.8847
C.V	11.23	Pred R-Square	0.7829
Press	6.580E-3	Adeq. Precision	11.896

As per the results, Fig. 4 and Fig. 5 for laser power and frequency input showed a similar trend which was that the HAZ values lowered as the input increased. Since combination AB input was found to be not significant (ANOVA), the interaction for both inputs were considered to be undefined. From the main effect plot, laser values of 50W and 150W, the HAZ values were 0.266 and 0.165 whilst with frequency input values of 1000Hz and 3000Hz, the HAZ values were found to be 0.273 and 0.157. It had been statistically shown that the laser power and frequency applied greatly influenced the HAZ output.

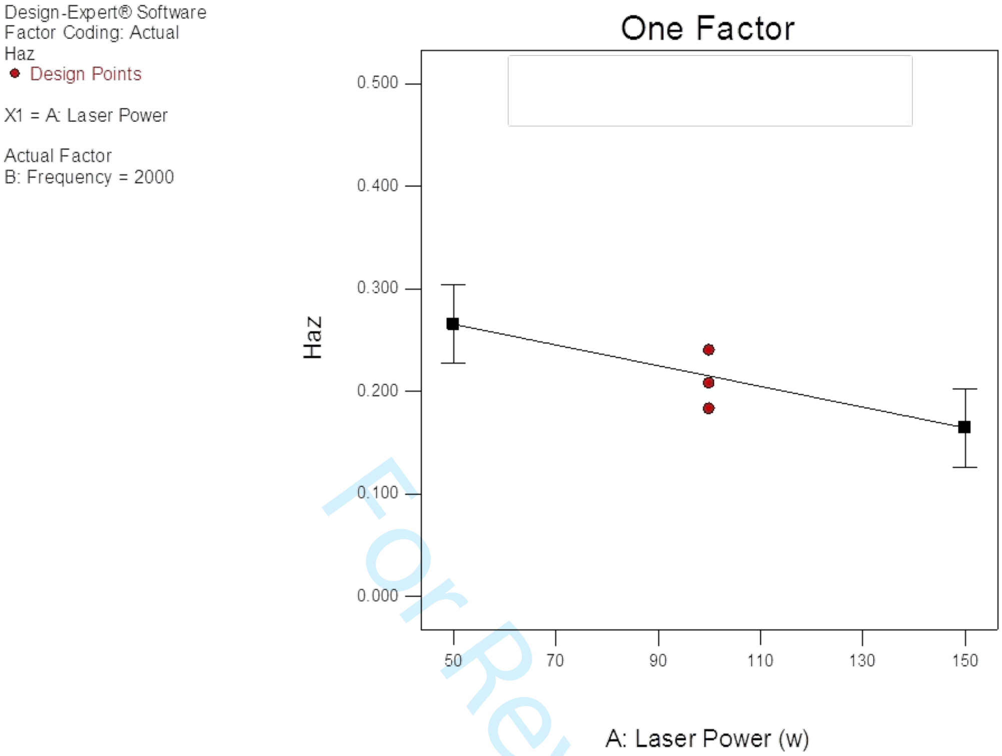


Fig 4. Main effect plot of laser power on HAZ

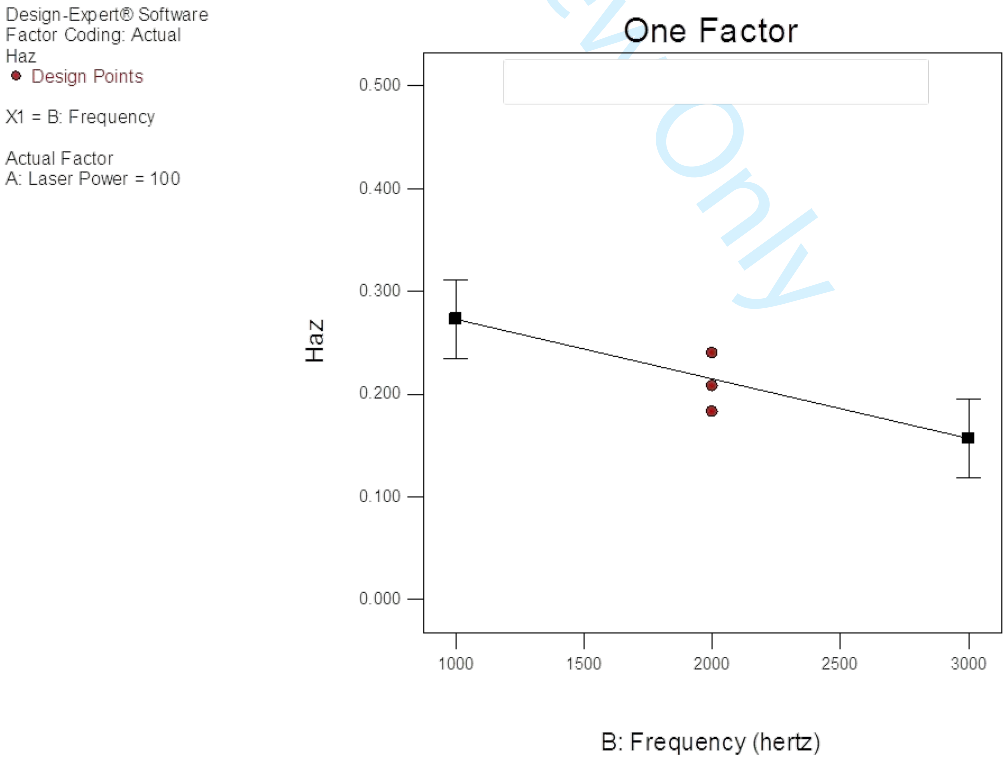


Fig 5. Main effect plot of frequency on HAZ

The results showed that HAZ decreases significantly with the increase in laser power and frequency, which was in agreement with the study reported by Bharatish et al [18]. This effect could be attributed to the following reason: as the laser power decreased, the width of HAZ increased due to the rapid temperature shrinkage produced by the increased thermal conductivity. As a result of the difference in cooling rate and thermal contraction between the surface and interior regions, excessive residual thermal strain occurred in and around the HAZ during laser drilling [19].

3.2 Microscopic images of the drilled hole

Figure 6 of the experimental data illustrated two surprising circumstances when laser drilling was unable to penetrate the material. Therefore, no penetration occurred in either process. This happened because the power used was too low such that melting and ablation processes did not occur in the alumina drilling area, otherwise the molten workpiece would solidify again and create a re-imprint layer on the side wall of the hole. Conversely, by increasing the laser power, a long waiting time was not required to reach the melting temperature of the material, so the material removal process would be good because it would reach the specified groove dimensions [20]. It had been previously reported that molten erosion of the sidewall of the pit is caused by high vapor pressure over the surface of the material at temperatures above 3000 K [9] , where during laser irradiation the pressure due to the high temperature will continue to move into the hole causing it to melt the front where molten material would come out of the hole [18][21]. As a result of observations made through SEM, the surface layer at the inlet and outlet holes was then measured to get the HAZ and Taper values.

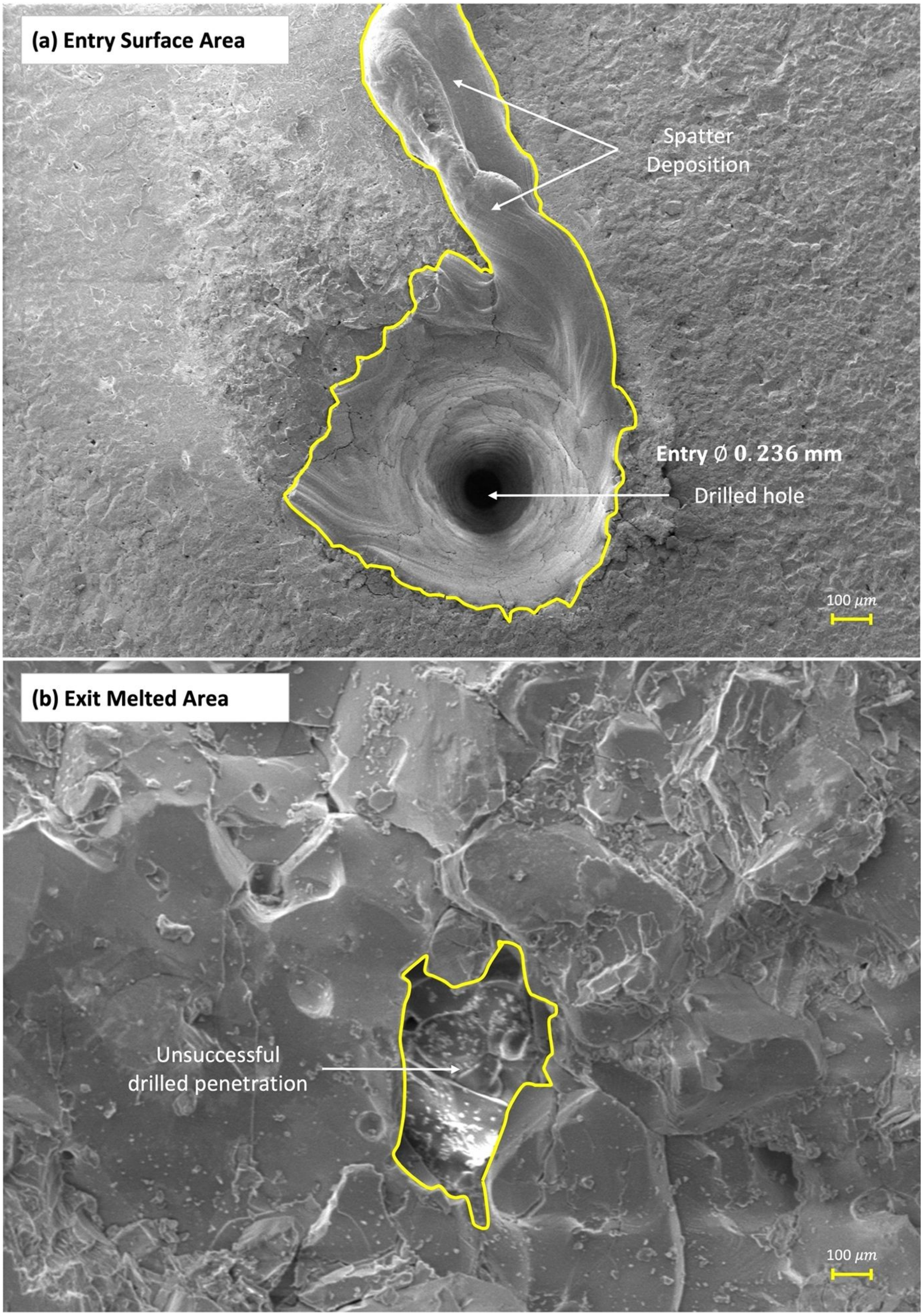
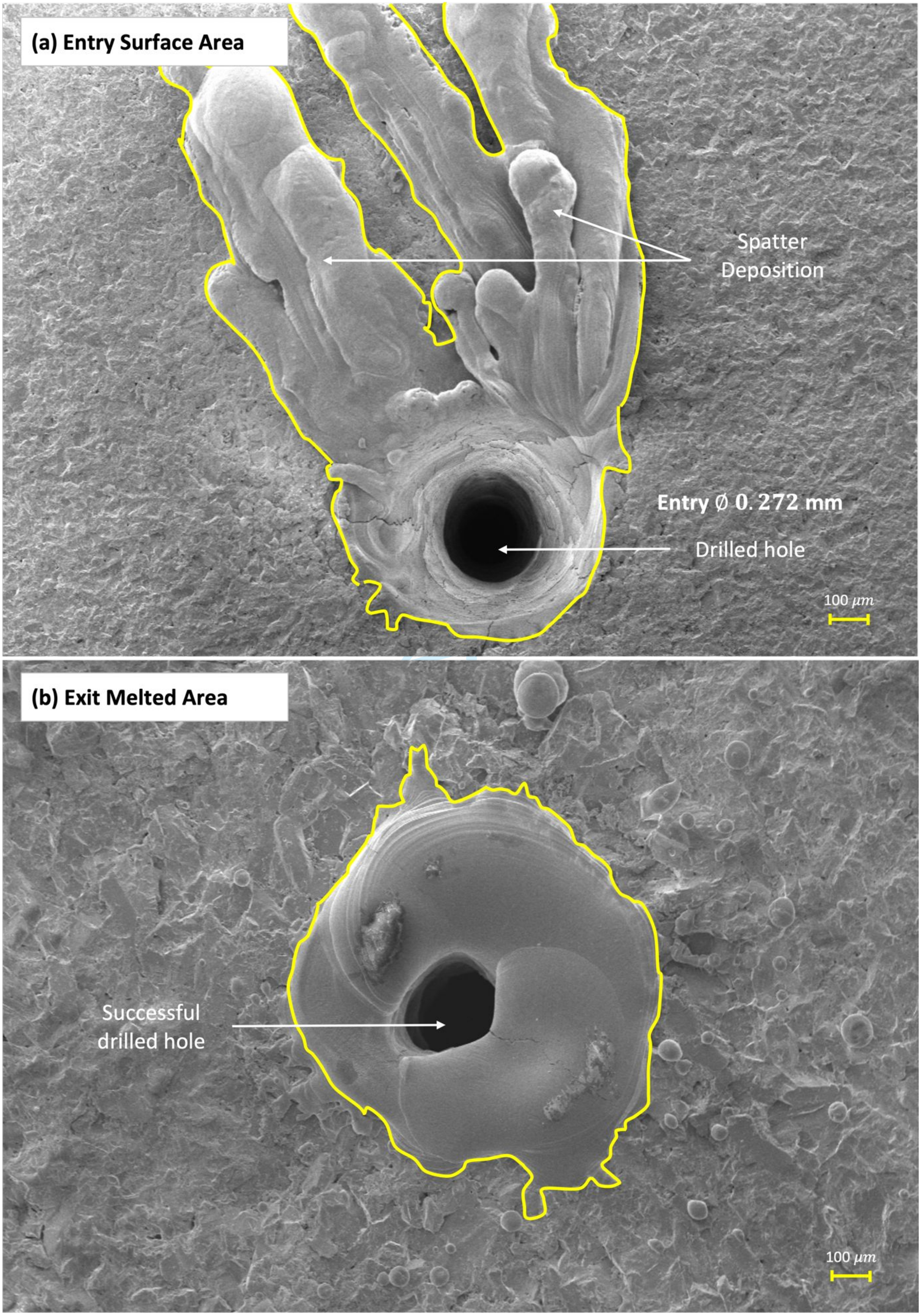


Fig. 6. Microscopic images of drilled hole; 50 W and 1000 Hz

198 

199 Fig. 7. Microscopic images of drilled hole; 100 W and 2000 Hz

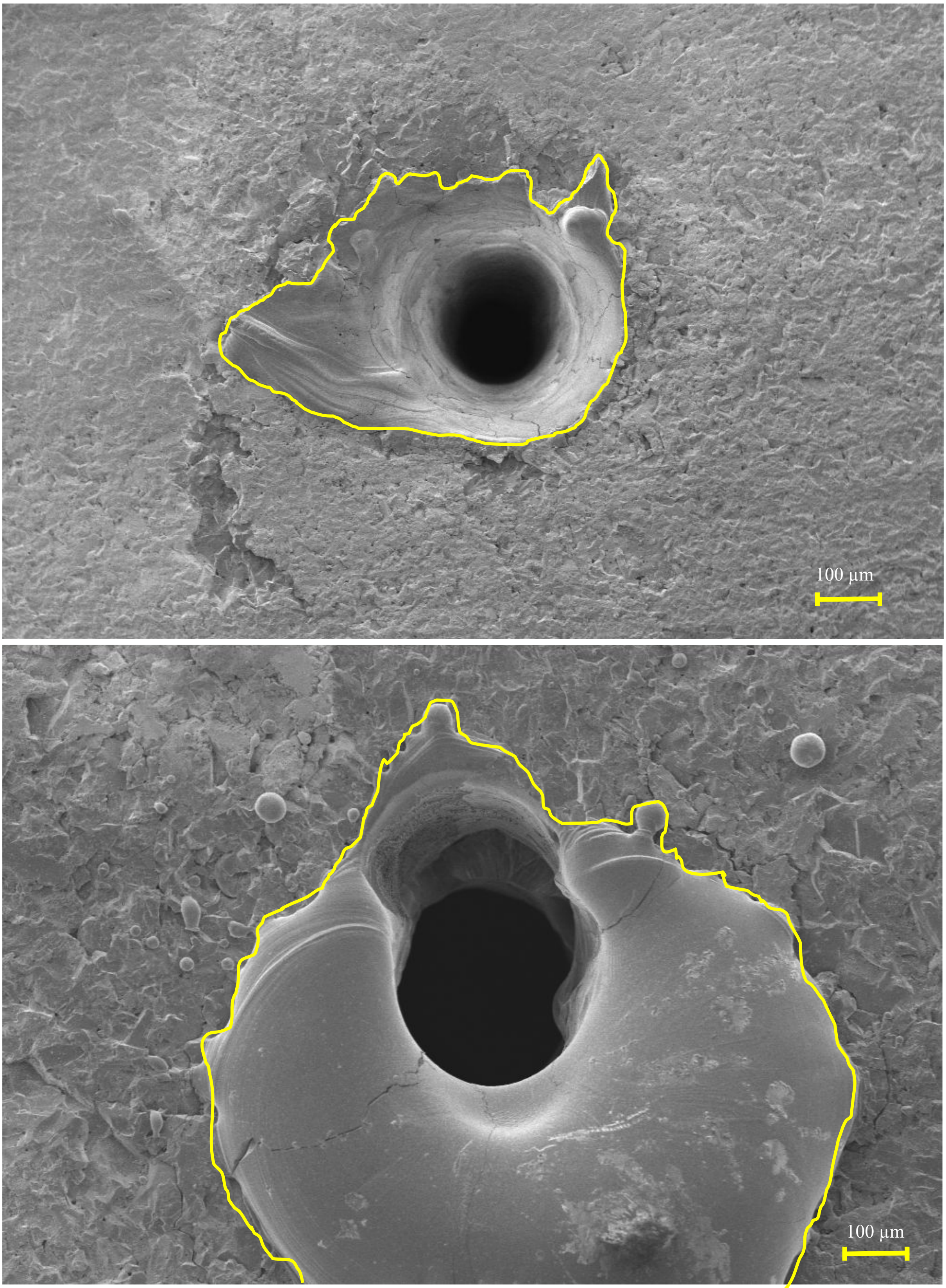


Fig. 8. Microscopic images of drilled hole; 150 W and 1000 Hz

Microscopic images taken by SEM show that laser power affects the profile of the inlet and outlet holes of the laser drilling with the change in machining parameters. The drilling had been successful, as shown in Fig. 7. From the observations, increasing the laser power can cause the diameter of the entry hole to be more significant. The laser power used in experiment 1 (Fig. 6) was 50 W, and the D_{min} was 0.236 mm, while the laser power used in experiment 5 (Fig. 7) was 150 W and the D_{min} was 0.272 mm. Due to the accumulation of thermal energy at peak power and higher absorptivity, the hole diameter increased with increasing laser power, further resulting in greater erosion at the hole entrance, which has been reflected in the HAZ and taper results. The image of experimental run 7 with a power of 150 W and a frequency of 1000 Hz, as seen in Figure 8, shows minimal recast material at the entry and exit holes. However, the objective of this research is not to minimize the recast layer, and it should be investigated in the future.

3.3 Effects of Laser Power (A) and Frequency (B) on taper angle

ANOVA analysis (Table 5) indicated that the model was significant with Prob> F of 0.0491. The only factor significantly impacting the taper angle was laser power (A) with Prob>F of 0.0200, whilst frequency (B) was found to be not significant with Prob>F 0.9407. The linear regression constructed by the model limited the interaction between AB. R-squared of 77.8% indicated that the developed model had a good correlation between the taper angle and the input parameters.

Table 5. ANOVA statistical analysis for taper angle response

Source	Sum of square	df	Mean Square	F Value	Prob>F	
Model	2.29	2	1.15	7.02	0.0491	Significant
A	2.29	1	2.29	14.04	0.0200	Significant
B	$1.024E^{-3}$	1	$1.024E^{-3}$	$6.273E^{-3}$	0.9407	Not Significant
Residual	0.65	4	0.16			
Lack Of Fit	0.53	2	0.26	4.26	0.1901	Not Significant
Pure Error	0.12	2	0.062			
Cor Total	2.95	6				

Std. Dev	0.40	R-squared	0.7784
Mean	1.25	Adj R-Squared	0.6675
C.V	32.23	Pred R-Square	0.1992
Press 2.36		Adeq. Precision	5.845

The results indicated that the taper angle decreased with increasing laser power but merely showed a stagnant trend when the frequency was increased (Fig. 5 and Fig. 6). The high power caused the material ablation rate to be reduced, resulting in a smaller exit hole and a bigger taper angle. This was consistent with a study by Bharatish and his team [18]. They found that the maintained frequency influenced the laser power and penetration time on the taper. The taper angle increased as the puncture time increased and reduced as the laser intensity increased. When the laser power increased on any frequency range between 1000Hz and 3000Hz, it reduced the taper angle value, which has been indicated in Fig 5 and Fig. 6.

From the main effect plot, laser power of 50W and 150W, the taper angle value was 2.011 and 0.497 while when frequency input was 1000Hz and 3000Hz, the taper angle was found to be 1.238 and 1.270. Statistically, it was show that the laser power greatly influenced the taper angle while frequency was found to be insignificant.

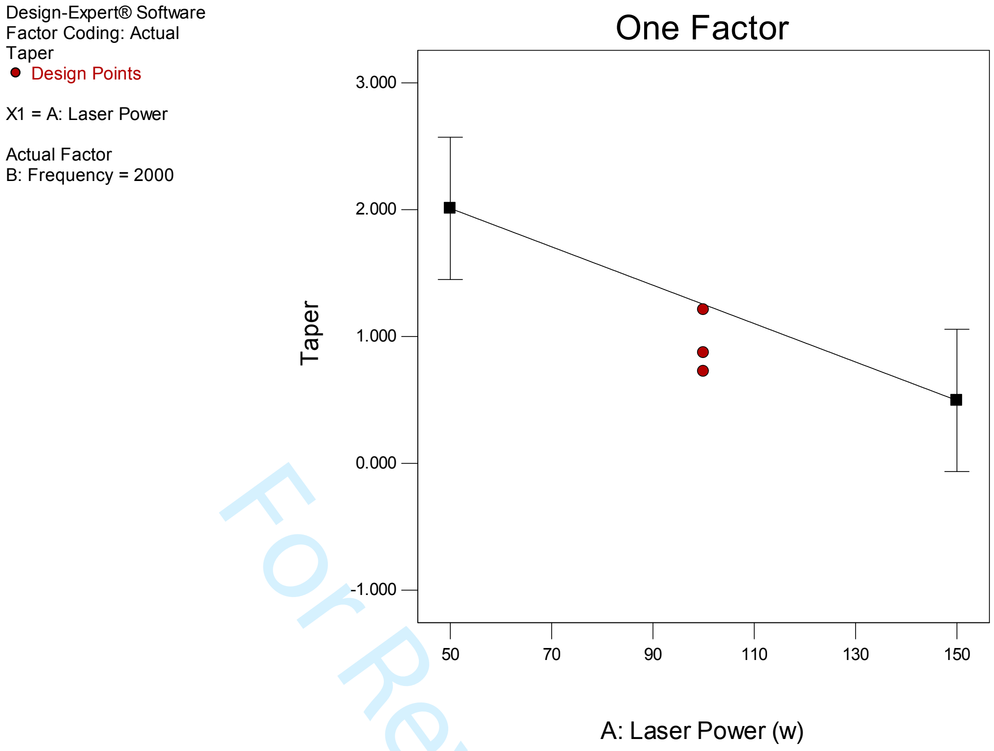


Fig. 5: Main effect plot of laser power on the taper angle

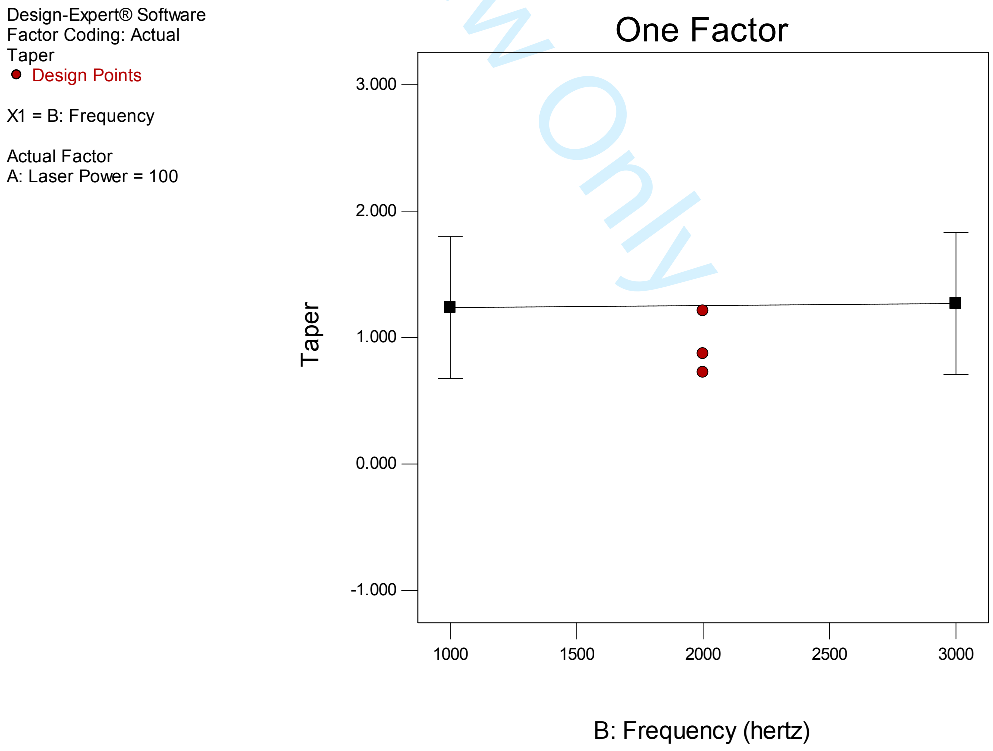


Fig. 6: Main effect plot of frequency on the taper angle

3.4 Parametric optimization on heat-affected zone and taper angle

The Minimum HAZ width and taper values had been obtained to determine optimal machining parameters. Further validation was also carried out to calculate the accuracy of the mathematical model by experiment. In this experiment, three different machining parameters were used for experiments with new laser power and frequency. It had been agreed that the laser power determines the HAZ and Taper effects. The value of the laser power of 150 W and the frequency of 1000 Hz had been obtained from the experimental results. To get the optimum conditions, it was necessary to run an experiment with different parametric combinations of laser power and frequency. The machining parameters were selected using an ANOVA analysis using the equations of (3) and (4) as follows:

$$HAZ = 0.572 - 2.41E^{-3}.\ A - 1.28E^{-4}\ .\ B + 0.7E^{-6}\ .\ A.B \quad (3)$$

$$Taper\ angle = 2.73557 - 0.01514\ .\ A + 1.6E^{-5}\ .\ B \quad (4)$$

where A is Laser power (W) and B is Frequensy (Hz).

Table 6. Percentage Of Error For HAZ and Taper Angle

Experiment			1	2	3
Parametric Input	Power (W)		130	150	149
	Frequency (Hz)		2700	1000	2956
Output Response	HAZ	Actual	0.166	0.196	0.154
		Predicted	0.158	0.187	0.142
		% Error	4.53	4.53	7.80
	Taper Angle	Actual	1.16	0.768	0.804
		Predicted	0.810	0.480	0.527
		% Error	37.68	59.81	52.56

Table 6 shows the validation process results with respect to the selected input parametric. The machining conditions with 149 W and 2956 Hz showed that the highest result for HAZ was still 0.154 mm, as well as for taper treatment, which was not significantly different. The error percentage for experiment 1 was 4.53%, while it was 4.53% for experiment 2 and 7.80% for experiment 3. HAZ had a 5.62% error rate on average. The taper was 37.68% in the 1st experiment, 59.81% in the 2nd and 52.56% in the 3rd. Tapers scored 50.5%. Based on the results of measurements of tapers with high percentage values, additional research was required and experimental data collection with other variables was still required. This was with the aim that better regression could be performed rather than just linear regression for this study.

4.0 Conclusions

A hole was successfully drilled with the use of a CO_2 laser while varying two parameters, laser power and frequency, with resulting HAZ size and taper angle. The diameters of the inlet, outlet and HAZ holes were measured using a scanning electron microscope (SEM). According to ANOVA analysis, the optimal process parameters for minimizing the width of HAZ were higher laser power (149 W) and higher frequency (2956 Hz). According to the ANOVA analysis, the probability value was less than 0.05, indicating a significant model term. HAZ-width increases with decreasing laser power and frequency. However, the taper angle increases as laser power decreases. Unlike the laser power, if a low frequency is used (e.g.: 1000 Hz), the taper angle value also decreases with high laser power. Low laser power (50 W) resulted in a small inlet diameter (0.236 mm), whereas high laser power (150 W) resulted in a larger inlet diameter (0.272 mm). Results from the microscopic images showed that low laser power (50W) would not result in penetration. The analytical prediction was in agreement with the experimental results with an error percentage value of 5.62%. However, for tapers, it is still necessary to conduct a more rigorous study involving others parameters or a significant amount of experimental research.

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Comments to the Author Reviewer: 1	
Experimental setup (Fig) is missing.	Has been included (Figure 1 & Fig 2)
Sub millimeter sized holes with lot of melted materials around, something wrong with machining parameters and values.	Figure 3 and figure 4 shows sample of SEM image of experimental run 1 and 3. Not all SEM images from the experiment have excessive melted materials around the hole. The nature of the DOE is that some of the parameter combinations will result in unoptimized result. Figure 3 Shows the SEM image of experimental run number 7 with minimal recast layer materials.
How to clean the spatter deposition as shown in Fig 3 and 4.	The spatter deposition (recast layer) is the manifestation of the parameter settings. Some of the experimental run result exhibit minimum spatter deposition as shown in the added image in Figure 8 It is expected some of the experimental runs in DOE to produce unoptimized result.
How the components in equation 1 and 2 are measured.	The explanation of the HAZ and taper angles are added with aids of Figures 3
How HAZ and taper angle as listed in Table 3 are measured.	The explanation of the HAZ and taper angles are added with aids of Figures 3
The measurement procedure for HAZ and taper angle are to be fully described.	The explanation of the HAZ and taper angles are added with aids of Figures 3
No schematic diagram given to explain the methodology	The experimental flow chart is added in Figure 2
SEM measurement is an estimation only and also not described	The SEM specification has been added.
Irregular hole diameter measurement is always inaccurate, so process to be fully explained.	Included in the procedure that for irregular hole, maximum diameter will be selected and used to calculate HAZ and taper angle. This statement has been added in the methodology section.

No SEM picture is shown for such measurement.	The measurement procedure of SEM image is as shown in Figure 3
Insufficient literature review.	The introduction has been improved to include literature review on the subject matter and additional references have been added. List of 10 additional references are :
Comments to the Author Reviewer: 2	
Please add some references	Additional references and added. 11 new reference are added: 2, 5, 6, 9, 10, 11, 13, 14, 7, 19, 21
Use the references in the range of ten years ago	We have deleted six references that are more than 10 years old and replace with the newer references.