Research Article

Experimental Analysis of Surface Roughness in the Cutting Process of Sugar Palm Fiber Reinforced Unsaturated Polyester Composites with Laser Beam and Abrasive Water Jet Cutting Technologies

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Abstract
This research aims to investigate the effects of the input parameters on the surface roughness as output parameters of CO_2 laser and abrasive water jet (AWJ) machining technologies utilized in cutting sugar palm fiber reinforced unsaturated polyester (SPF-UPE) composite of three specimen thicknesses. The objective of this study is to collect data involve the optimal parameters of these technologies regarding the surface roughness response. The motive was to avoid defects arising use in the conventional cutting techniques. In the AWJ technique, stand-off-distance, traverse speed, and water pressure were chosen as variable input parameters to optimize the surface roughness, whereas laser power, traverse speed, and gas pressure were the variable input parameters in the CO_2 laser cutting technique. Taguchi's approach was used to estimate the input parameter's levels that produce the best surface roughness. Analysis of variation (ANOVA) was used to determine the contribution of every single input processing parameter to the effect on the surface roughness response. Good surface roughness responses could be attained by applying the optimum input parameters determined in this study. The experimental results of the current research provide practical data for the cutting of SPF-UPE composites with CO_2 laser and AWJ machining techniques, and the findings can be used as a good starting point for the testing of other similar composites under the same cutting conditions

Keywords: Surface roughness, Laser beam, Water jet, Input parameters, Natural fiber composites

1 Introduction

Natural fiber reinforced polymers have gained increased attention as an applicable alternative to synthetic fiber composites, owing to the growing need for lightweight materials and low environmental impacts [1]–[4]. Natural fiber reinforced polymers also have some significant advantages, such as their low cost, low density, and ease of manufacturing; furthermore, the reinforcement fibers are derived from renewable resources, as no energy is required for their creation, in contrast to the synthetic fibers [5]–[8]. SPF-UPE composite is one of the most promising composites, exhibiting good physical and chemical properties according to numerous studies, which have been done to evaluate them [6], [9]–[17]. Therefore, due to the good properties of SPF-UPE composite, it is suitable for a variety of technical applications, such as automobiles, aircraft, construction, marine, packaging, electronic industries, sporting equipment and so forth [6], [13], [18].

Despite the fact that the composites are made close to near-net shape, secondary processing is often needed. Machining processes, such as profiling, trimming, drilling and sawing are used to produce the final shape of the product with improved dimensional precision [19]–[23]. Because of the heterogeneous nature of natural fiber reinforced polymers and the cutting forces associated with traditional cutting techniques as well as the fixing process of the workpiece that needs relatively high clamping forces, numerous serious flaws emerge with the use of conventional cutting methods, such as material damage, poor surface quality, fiber fraying, dimensional instability, and delamination [24]–[29]. In order to overcome these challenges or reduce their impacts, alternative non-traditional machining technologies have been considered [21], [30]. Two of the most prominent techniques that have been worked on to overcome the defects resulting from the traditional cutting methods are AWJ and CO_2 laser machining techniques, owing to their relatively high precision and productivity compared to other unconventional technologies [31]. The AWJ is a modern, environmentally friendly technique used to cut a broad spectrum of hard and soft materials without thermal deformations or residual stresses. AWJ has several important advantages, such as the low fixing force, low accompanying cutting forces, no generated heat, no smoke or gases released, good surface finishing with high accuracy, and a fully automated process [31], [32].

Laser cutting technology is an advanced technique used to cut a wide range of materials with high efficiency, productivity, and accuracy. The process is non-contact and does not require a large fixture. Laser beam cutting technology has other significant advantages, such as the produced kerf width being extremely small, fully automated and rapid process and the heat-affected zone is relatively low [13], [31]. The surface quality is one of the most significant output parameters from cutting processes in general, as the surface roughness is desired to be as low as possible in most processes, and it represents one of the most important determinants of cutting process quality [33]. Surface roughness is mainly influenced and controlled by the values of some input processing parameters in laser beam and water jet cutting processes; thus, the surface roughness can be improved by optimizing the input processing parameters [33].

Based on the literature and the recent survey [31], there is no study dealing with SPF-UPE composites in terms of improving the surface quality resulting from unconventional cutting techniques, and this type of experimental study on natural fiber reinforced polymers is extremely limited in general, especially regarding CO_2 laser cutting process, and most of the previous studies have not covered a broad range of input parameter values, and most of them dealt with one thin material thickness [31], which represents a limitation in the available data related to the cutting of natural fiber composites with unconventional technologies. In this context, a number of theoretical and statistical studies have also been conducted that aimed to develop mathematical models through, which the values of the output parameters are predicted based on the inputs of the process. Alberdi *et al.* [34] worked on generalizing a mathematical model that was formulated by Zeng [35] to include glass fiber reinforced polymer composites cut with AWJ by finding the machinability index experimentally and developing the mathematical model to suit the studied composites to predict surface roughness and kerf properties. Jagadish *et al.* [36] worked on the formulation of mathematical models that predicted the surface roughness and the processing time required for the process of cutting green composites with AWJ and then compared the results with the experimental results. They concluded that the mathematical models can be used as a systematic framework model to predict the targeted outputs, and also to help in the selection of the optimum input parameters. Eltawahni *et al.* [37] formulated statistical models to adapt the processing parameters to obtain the best response to kerf properties and surface roughness in the cutting process of MDF with a CO_2 laser by comparing the predicted results with the experimental records. The statistical models achieved acceptable and reliable results for cutting the same material.

Most of the theoretical and statistical studies in this field were conducted on composites reinforced with synthetic fibers. In order to generalize the formulated mathematical models in the field of natural fiber composites, many theoretical studies need to be conducted to modify or reformulate those models and compare their outputs with experimental outputs. The current study was performed to address the need to optimize the parameters for the desired surface quality in the cutting process of SPF-UPE composites with CO_2 laser and AWJ machining techniques. This experimental study focuses on the investigation and analysis of the impact of effective input parameters on the surface roughness response in the cutting of three various plate thicknesses (2, 4, and 6 mm) of SPF-UPE composite using CO_2 laser and AWJ cutting techniques in order to acquire sufficient data regarding the desired surface quality. Thus, the present study is novel in that it uses and suggests optimal cutting conditions to obtain a desired surface roughness response in the cutting process of SPF-UPE composite with CO_2 laser and AWJ machining technologies, in addition to displaying and evaluating the serious defects resulting from the application of inappropriate levels of the input parameters in both cutting processes.

2 Materials and Methods

2.1 *Fabrication of the composite*

The tested material in the current research was SPF-UPE composite. Sugar palm fibers (SPFs) were washed using pure water, dried with hot air, and then immersed in 0.25 M/L NaOH solution for one hour to improve the physical and mechanical properties of the SPFs [12], [38] and the natural fibers in general [39]. The average aspect ratio of the fibers was 25. The fibers were manually cut into lengths of 5 to 10 mm. The matrix used was unsaturated polyester (UPE) with a 30% fiber loading, as the composites with this fiber content demonstrated good physical and mechanical properties [14], [40], [41]. Three different depth molds were made to create three different specimens with thicknesses of 2, 4, and 6 mm, lengths of 210 mm, and widths of 120 mm. The prepared molds were initially coated with a release agent (wax). The composite specimens were created using the hand-lay-up technique. The molds were disassembled and the specimens were removed after they had been placed under a 40 kg weight for 24 h.

2.2 *Experimental setup*

The experiments of the laser beam cutting were

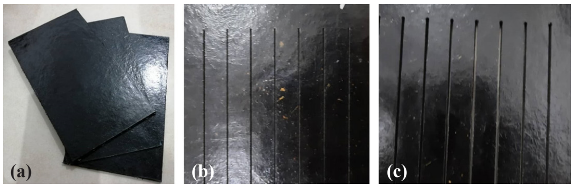

Figure 1: (a) The composite specimens before cutting processes. (b) Specimen cut with Laser beam cutting technology. (c) Specimen cut with abrasive waterjet cutting technology.

conducted using a CO_2 laser cutting machine (AMADA FO 3015 M2 NT, Buena Park, CA, USA) equipped with a CNC worktable and a maximum output power of 4000 W with 1500 Hz pulsed mode. A 7.5” focal length lens was used to concentrate the laser beam onto the top surface of the material. The nozzle stand-off-distance was 1.5 mm, the nozzle diameter was 2 mm, and the air was used as the assist gas. The input parameters were the traverse speed, assist gas pressure, and laser power because they had substantial impacts on surface roughness [31], [37], [42]–[44]. Other parameters were held constant, such as the focal length, nozzle diameter, and nozzle stand-off space. The different values of the input parameter were used to test three plate thicknesses of 2, 4, and 6 mm. The AWJ cutting process was conducted using (Flow Mach2 1313B Kent, Washington 98032 · USA) CNC waterjet machine with a working water pressure of up to 60 kpsi and a nozzle traverse speed of up to 10 m/min. The experiments were performed using garnet abrasive grains with a mesh size of 80 (177 μm), and a 1 mm nozzle diameter with an impact angle of 90°. The water pressure, traverse speed, and stand-off-distance were taken as the variable input parameters, where they exhibited a significant impact on the surface roughness response [31], [45]–[48]. By varying the input parameter values, three different plate thicknesses of 2, 4, and 6 mm were tested under AWJ machining conditions. Figure 1 shows the produced composite specimens before and after cutting processes.

2.3 *Cutting parameter selection*

With a fixed gas pressure of 2 bar, full thru cutting parameters (FTC) were found for four different laser power levels of 100, 1000, 2000, and 3000 W. The traverse speed was then adjusted until the cut was completed in full thru, and this was performed for all thicknesses. As a consequence, four sets of parameters were derived for each thickness. Cases, in which no full cut, were achieved at any cutting speed were eliminated. Three levels were chosen for every single parameter, in which the full thru cut, was achieved. Then, using the L9 Taguchi array arrangement, nine cuts of 60 mm length and a spacing gap of 10 mm were made at various levels for the input parameters. The experiments required three plates for each thickness of material manufactured with the dimensions mentioned in Section 2.1. 18 cuts can be made on every plate, and thus a total of 9 plates were made to perform the CO_2 laser cutting process. Damaged specimens, deep heat-affected zones, and uneven cuts that were produced by high laser power were excluded. Furthermore, tests that resulted in low productivity owing to low cutting speeds were also excluded. For the investigation and optimization, work pieces with regular cuts, no observable damages, and a low depth of heat-affected zone were chosen. The values of the input parameter for every single thickness in the laser beam cutting technique are shown in the Tables 1–3.

Table 1: Input parameters and their levels for the CO_2 laser machining conditions of a 2 mm plate thickness

Parameters	Level 1	Level 2	Level 3
Laser Power (W)	200	300	400
Traverse Speed (mm/min)	150	200	250
Gas Pressure (bar)	2	3	4

Table 2: Input parameters and their levels for the CO_2 laser machining conditions of a 4 mm plate thickness

Parameters	Level 1	Level 2	Level 3
Laser Power (W)	1000	1300	1600
Traverse Speed (mm/min)	5600	5800	6000
Gas Pressure (bar)	2	3	4

Table 3: Input parameters and their levels for the CO_2 laser machining conditions of a 6 mm plate thickness

Parameters	Level 1	Level 2	Level 3
Laser Power (W)	2000	2300	2600
Traverse Speed (mm/min)	7600	7800	8000
Gas Pressure (bar)	2	3	4

In the waterjet cutting technique, the traverse nozzle speed, stand-off-distance, and water pressure were chosen as the variable parameters. The other factors such as the nozzle diameter, abrasive grain size, and impact angle remained constant. The AWJ machining process enables the cutting of a wide variety of thick and hard materials, and SPF-UPE is a soft material in comparison to the capabilities of the AWJ cutting process. Hence, a complete through cut was obtained at low water pressures (100–200 MPa) and high cutting speeds. Despite this, visible flaws such as damage and cracks appeared on the specimens at high traverse speeds and low water pressures. Fiber pull-out and incomplete cutting were two other types of defects that occurred in the cutting zone under identical operating water pressure and nozzle traverse speed conditions. Additionally, the extensive propagation of the kerf zone was a prominent defect that appeared when using high traverse nozzle speeds and low water pressures which also caused zigzag cuts. Therefore, the levels of the parameters demonstrating the aforementioned flaws were not considered in the optimization of the surface roughness response. The best-obtained cuts were recorded at relatively high water pressures, from 300 to 340 MPa, with corresponding cutting speeds for each specimen thickness. The range of stand-off distances from 1 to 3 mm was the best, based on related previous works. Thus, using an L9 Taguchi array arrangement, nine cuts of 60 mm length and a spacing gap of 10 mm were used at various levels for the input parameters. The experiments required three plates for each thickness of the material, manufactured with the dimensions mentioned in Section 2.1. Eighteen cuts can be made on every plate, and thus a total of nine plates were made to perform the AWJ cutting process. The levels of the input parameter for each material thickness in the AWJ machining operation are shown in the Tables 4–6.

Table 4: Input parameters and their levels for the AWJ machining conditions of a 2 mm plate thickness

Parameters	Level 1	Level 2	Level 3
Water Pressure (MPa)	300	320	340
Traverse Speed (mm/min)	2400	2600	2800
Stand-off-Distance (mm)	1	2	3

Table 5: Input parameters and their levels for the AWJ machining conditions of a 4 mm plate thickness

Parameters	Level 1	Level 2	Level 3
Water Pressure (MPa)	300	320	340
Traverse Speed (mm/min)	1800	2000	2200
Stand-off-Distance (mm)	1	2	3

Table 6: Input parameters and their levels for the AWJ machining conditions of a 6 mm plate thickness

Parameters	Level 1	Level 2	Level 3
Water Pressure (Mpa)	300	320	340
Traverse Speed (mm/min)	1200	1400	1600
Stand-off-Distance (mm)	1	2	3

2.4 *The measurements*

The average roughness (Ra) of the machined surface was measured using a (Mahr Perthometer S2, Mahr GmbH Göttingen, Germany) according to the standards (DIN EN ISO 3274, e.g., band-pass filter). The surface roughness readings were taken three times at various places to obtain the average data for each specimen along the cutting edge, as the direction of the measurement stylus movement was parallel to the cutting direction. A specimen of 60 mm in length and 10 mm in width was cut, and then the surface roughness was measured for every single case. The imaging tests were performed by a reflected industrial microscope OLYMPUS BX51M system with (Olympus Stream Essentials 2.5, Shinjuku-ku, Tokyo, Japan) image analysis software.

2.5 *Optimization methods*

The Taguchi approach was used to examine the effect of the input parameters on the surface roughness response (Ra), as the measured average values of the surface roughness were analyzed based on signal-to-noise ratio (S/N) small-is-better calculations to determine the levels of the input parameters that produce the best response of the average surface roughness. It was also to estimate the ranking of significance for every single input parameter in both cutting techniques. The analysis of variance (ANOVA) approach was used to determine the contribution of each input parameter to the effect on the surface roughness response. The statistical analyses were carried out using the Minitab 17 software, State College, PA, USA.

3 Results and Discussion

3.1 *CO_2 laser cutting process*

The input parameter ranges that resulted in the defects illustrated in Figure 2 were excluded from the investigation. The levels of the input parameters listed in Tables 1–3 were evaluated for the investigation and optimization of the surface roughness in the cutting process of SPF-UPE composites with CO_2 laser cutting technology.

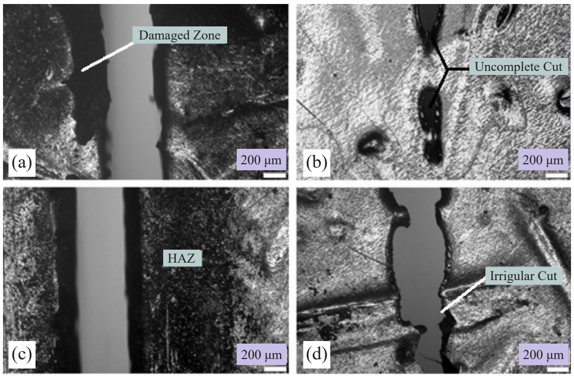

Figure 2: (a) Damaged cutting zone. (b) Uncompleted cut. (c) High propagated heat-affected zone (HAZ). (d) Irregular cut.

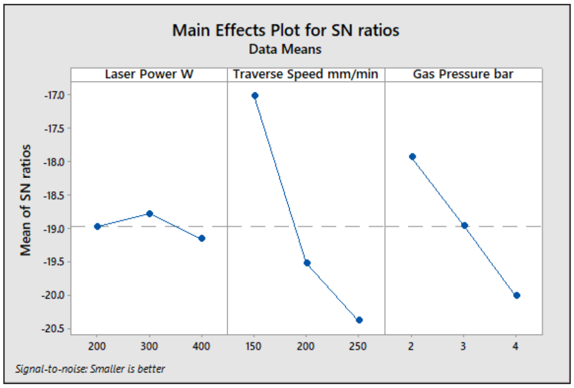

Figure 3: Average S/N ratio of the input cutting parameters of a 2 mm material thickness of SPF-UPE composite cut with the CO_2 laser cutting technique.

The average S/N ratio for the input parameter was calculated and displayed in Figure 3 using the average surface roughness responses listed in Table. 7 for a plate thickness of 2 mm. Under these input parameters, the combination of low gas pressure and traverse speed produced the optimal surface roughness response, and no considerable influence of laser power was observed. Eltawahni *et al.* [37] also found that the low levels of traverse speeds and gas pressures gave the best surface roughness in the cutting of MDF with the same cutting technique. Based on the calculated max-min variance of the S/N ratio listed in Table 8, the significance of the variable processing inputs was determined, as the traversal speed was the most significant factor affecting the average surface roughness, followed by the assist gas pressure and laser power, respectively. According to the ANOVA calculations displayed in Table 9, the input parameters' contributions to the effect on average surface roughness were 70.27% for traverse speed, 25.55% for gas pressure, and 0.97% for laser power. From Figure 3, 150 mm/min traverse speed, 2 bar assist gas pressure, and 300 W laser power were the optimal input processing parameters for cutting a 2 mm thickness of the SPF-UPE composite cut using the CO_2 laser beam cutting technique regarding the desired response of the average surface roughness. Because of the minimal contribution of laser power variation, the different levels are listed in Table 1 can be applied with no significant effect.

Table 7: Experiments' orthogonal array L9, the measured surface roughness (Ra), and the calculated signal-to-noise (S/N) ratio based on the Taguchi approach for a 2 mm plate thickness of SPF-UPE cut with the CO_2 laser cutting technique

Ex no:	Laser Power (W)	Traverse Speed (mm/min)	Gas Pressure (bar)	Average Surface Roughness (Ra) µm	S/N Ratio
1	200	150	2	6.01	–15.5775
2	200	200	3	9.50	–19.5545
3	200	250	4	12.30	–21.7981
4	300	150	3	7.21	–17.1587
5	300	200	4	9.98	–19.9826
6	300	250	2	9.12	–19.1999
7	400	150	4	8.20	–18.2763
8	400	200	2	8.94	–19.0268
9	400	250	3	10.20	–20.1720

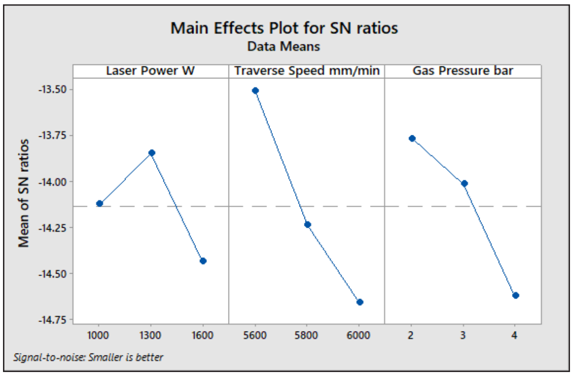

Figure 4: Average S/N ratio of the input cutting parameters of a 4 mm material thickness of SPF-UPE composite cut with the CO_2 laser cutting technique.

Table 8: S/N ratio response table of a 2 mm thickness of SPF-UPE composite cut with the CO_2 laser cutting technique

Level	Laser Power (W)	Traverse Speed (mm/min)	Gas Pressure (bar)
1	–18.98	–17.00	–17.93
2	–18.78	–19.52	–18.96
3	–19.16	–20.39	–20.02
Delta	0.38	3.39	2.08
Rank	3	1	2

The effect of the process control parameters on the surface roughness in the case of a 4 mm specimen thickness is illustrated in Figure 4 by computing the S/N ratio based on the surface roughness response data listed in Table 10 It is clear that the optimum response of the surface roughness can be acquired by applying a blend of a low cutting speed, medium laser power, and low assist gas pressure. Based on the max-min

Table 9: ANOVA results for surface roughness response of a 2 mm material thickness cut by the CO_2 laser cutting technique

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	*F*-Value	*P*-Value
Laser Power (W)	2	0.007198	0.97%	0.007198	0.003599	0.30	0.769
Traverse Speed (mm/min)	2	0.523946	70.27%	0.523946	0.261973	21.86	0.044
Gas Pressure (bar)	2	0.190500	25.55%	0.190500	0.095250	7.95	0.112
Error	2	0.023968	3.21%	0.023968	0.011984		
Total	8	0.745612	100.00%				

variance calculation in Table 11, traverse speed is still the most important factor influencing surface roughness, followed by gas pressure and laser power, respectively, similarly to the case of 2 mm material thickness. However, it is noticeable that the contribution of the laser power increased at the expense of both other parameters according to the contribution of the inputs computed in Table 12. From Figure 4, the optimum response of the surface was attained at 1300 W laser power, 5600 mm/min traverse speed, and 2 bar assist gas pressure.

Table 10: Experiments' orthogonal array L9, measured surface roughness (Ra) and calculated signal-to-noise (S/N) ratio based on the Taguchi approach for a 4 mm plate thickness of SPF-UPE cut with the CO_2 laser cutting technique

Ex no:	Laser Power (W)	Traverse Speed (mm/min)	Gas Pressure (bar)	Average Surface Roughness (Ra) µm	S/N Ratio
1	1000	5600	2	4.60	–13.2552
2	1000	5800	3	5.01	–13.9968
3	1000	6000	4	5.70	–15.1175
4	1300	5600	3	4.51	–13.0835
5	1300	5800	4	5.35	–14.5671
6	1300	6000	2	4.95	–13.8921
7	1600	5600	4	5.12	–14.1854
8	1600	5800	2	5.10	–14.1514
9	1600	6000	3	5.60	–14.9638

In the case of a 6 mm specimen thickness, Figure 5 displays the average values of the S/N ratio for every single level of input processing factor based on the surface roughness responses listed in Table 13 Under these conditions of control parameters and material thicknesses, minimum speeds, a low assist gas pressure

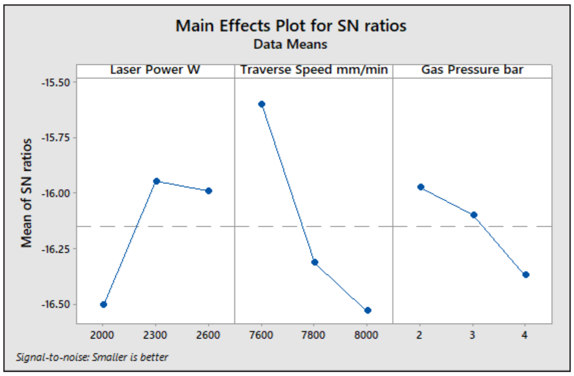

Figure 5: Average S/N ratio of the input cutting parameters of a 6 mm material thickness of SPF-UPE composite cut with the CO_2 laser cutting technique.

Table 11: S/N ratio response table of a 4 mm thickness of SPF-UPE composite cut with the CO_2 laser cutting technique

Level	Laser Power (W)	Traverse Speed (mm/min)	Gas Pressure (bar)
1	–14.12	–13.51	–13.77
2	–13.85	–14.24	–14.01
3	–14.43	–14.66	–14.62
Delta	0.59	1.15	0.86
Rank	3	1	2

and a medium level of laser power produced the optimal response of the surface roughness. Based on the max-min variation calculations presented in Table 14 and the ANOVA calculations are presented in Table 15, traverse speed is still the most important parameter influencing the surface roughness response, with a contribution of 56.12%, whereas laser power came second, with an increase in its contribution to 20.75% at the expense of the contribution of the assist gas

Table 12: ANOVA results for the surface roughness response of a 4 mm material thickness cut by the CO_2 laser cutting technique

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	*F*-Value	*P*-Value
Laser Power (W)	2	0.22598	15.46%	0.22598	0.112992	13.11	0.071
Traverse Speed (mm/min)	2	0.80059	54.76%	0.80059	0.400295	46.45	0.021
Gas Pressure (bar)	2	0.41830	28.61%	0.41830	0.209148	24.27	0.040
Error	2	0.01724	1.18%	0.01724	0.008618		
Total	8	1.46211	100.00%				

pressure, which came third with a limited contribution of 6.50%. From Figure 5, the optimal inputs of the controlling parameters that gave the best surface roughness were 7600 mm/min traverse speed, 2300 W laser power, and a 2 bar assist gas pressure.

Table 13: Experiments' orthogonal array L9, measured surface roughness (Ra) and calculated signal-to-noise (S/N) ratio based on the Taguchi approach for a 6 mm plate thickness of SPF-UPE cut with the CO_2 laser cutting technique

Ex no:	Laser Power (W)	Traverse Speed (mm/min)	Gas Pressure (bar)	Average Surface Roughness (Ra) µm	S/N Ratio
1	2000	7600	2	6.26	–15.9315
2	2000	7800	3	6.54	–16.3116
3	2000	8000	4	7.31	–17.2783
4	2300	7600	3	5.97	–15.5195
5	2300	7800	4	6.67	–16.4825
6	2300	8000	2	6.20	–15.8478
7	2600	7600	4	5.86	–15.3580
8	2600	7800	2	6.42	–16.1507
9	2600	8000	3	6.66	–16.4695

Table 14: S/N ratio response table of a 6 mm thickness of SPF-UPE composite cut with the CO_2 laser cutting technique

Level	Laser Power (W)	Traverse Speed (mm/min)	Gas Pressure (bar)
1	–16.51	–15.60	–15.98
2	–15.95	–16.31	–16.10
3	–15.99	–16.53	–16.37
Delta	0.56	0.93	0.40
Rank	2	1	3

Figure 6 illustrates the influence of the tested inputs on the surface roughness response of each specimen thickness. The traverse speed represents the highest contributing factor to the effect on surface roughness response in all cases of material thicknesses; however, the greatest effect of the traverse speed was in the case of a 2 mm specimen thickness, and it decreased in the cases of medium and larger thicknesses. In the case of a 2 mm thickness, the change in the laser power had no significant contribution to the surface roughness; therefore, it is possible to apply either of the other two values of laser power without expecting a significant effect on the surface roughness response. However, the effect of the laser power gradually increased with the increase in the material thickness, and it became the second factor in terms of influencing the surface roughness in the case of a 6 mm plate thickness. Gas pressure had a considerable influence on the surface roughness in the experiments on 2 and 4 mm plate thicknesses, but it had no important effect in the case of a 6 mm plate thickness, and this is consistent with Solati *et al.* [44], where the most important factors affecting surface roughness were traverse speed and laser power. In all cases of material thicknesses, the best response of the surface roughness was achieved by applying low traverse speeds, which might be explained as low levels of traverse speed providing a sufficient duration for the thermal decomposition of the material at the cutting area, which led to the removal of targeted material entirely by the flowing compressed gas without any residual material remaining in the cutting area due to high traverse speeds that might cause a negative effect on the surface quality.

Table 15: ANOVA results for the surface roughness response of a 6 mm material thickness cut by the CO_2 laser cutting technique

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	*F*-Value	*P*-Value
Laser Power (W)	2	0.000017	20.75%	0.000017	0.000008	1.25	0.445
Traverse Speed (mm/min)	2	0.000045	56.12%	0.000045	0.000022	3.37	0.229
Gas Pressure (bar)	2	0.000005	6.50%	0.000005	0.000003	0.39	0.719
Error	2	0.000013	16.64%	0.000013	0.000007		
Total	8	0.000080	100.00%				

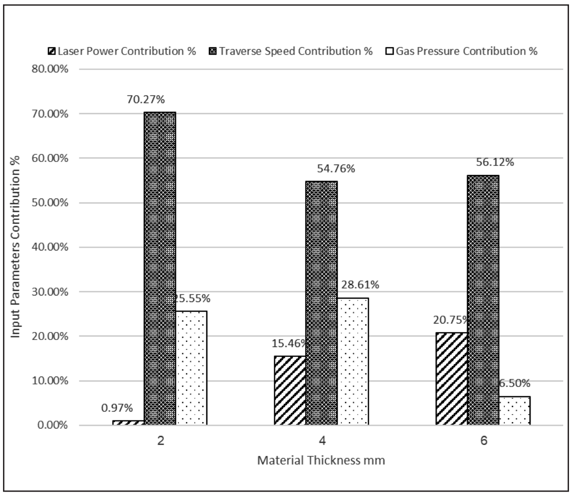

Figure 6: Input parameter contributions to the surface roughness of the different material thicknesses of SPF-UPE composite cut with the CO_2 laser cutting technique.

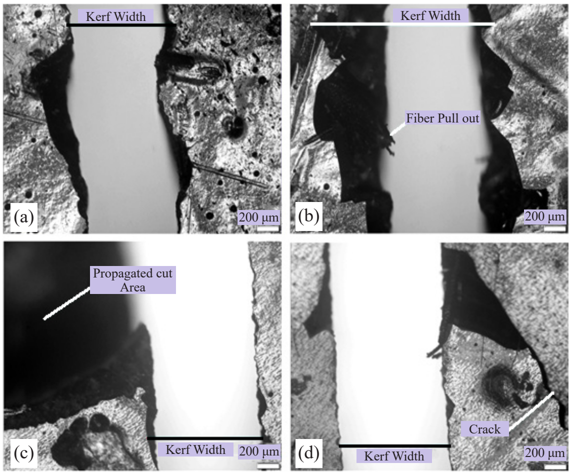

Figure 7: (a) Uneven cut. (b) Pull out of the fibers. (c) Highly extended cutting area. (d) Cracks and damage at the cutting zone.

3.2 *Abrasive water jet cutting process*

In order to optimize the surface roughness response in the cutting process of SPF-UPE composite cut using AWJ machining technology, the ranges of the input parameter that resulted in the defects illustrated in Figure 7 were excluded. The levels of the controlling parameters in Tables 4–6 that produced a satisfying quality of cutting kerfs were optimized.

Regarding the surface roughness response listed in Table 16 for a 2 mm specimen thickness cut using the AWJ machining technique, the average S/N ratio for every single input parameter was estimated and displayed in Figure 8. A combination of low levels of all of the input parameters produced the best response of the surface roughness, as illustrated in Figure 8, and this result is consistent with what Prabu *et al.* [45] found when examining a banana fiber reinforced unsaturated polyester cut using an abrasive water jet machining process, and what Sumesh *et al.* [47] found when they tested a sisal/pineapple epoxy hybrid composite cut with the same technique. In accordance with the calculated max-min difference of the S/N ratio displayed in Table 17, the importance of the inputs can be determined; the traverse speed ranked first as the most important input parameter affecting surface roughness in accordance with the results found by Dhakal *et al.* [49]. The effect of the water pressure and stand-off-distance on the surface roughness ranked second and third, respectively. The ANOVA calculations displayed in Table 18 show a significant contribution of the nozzle traverse speed—52.62%—to the influence on surface roughness, whereas the contribution of the water pressure was 28.63%, and the stand-off-distance was the least contributing factor, as it was 16.28%. The optimal response of the surface roughness was produced by applying a 300 MPa operating water pressure, 2400 mm/min traverse nozzle speed, and 1 mm stand-off distance.

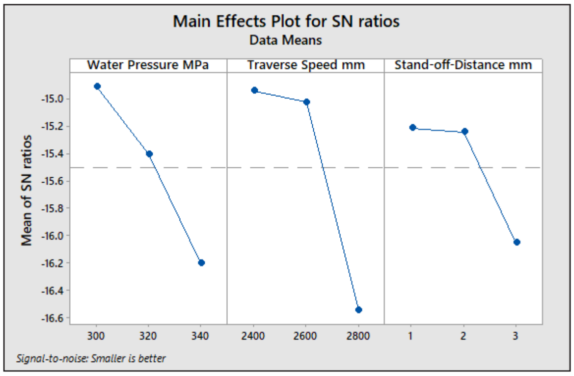

Figure 8: Average S/N ratio of the input cutting parameters of a 2 mm material thickness of SPF-UPE composite cut with the AWJ cutting technique.

Table 16: Experiments' orthogonal array L9, measured surface roughness (Ra), and calculated signal-to-noise (S/N) ratio based on the Taguchi approach for a 2 mm plate thickness of SPF-UPE cut with the AWJ cutting technique

Ex no:	Water Pressure (MPa)	Traverse Speed (mm/min)	Stand-off-Distance (mm)	Average Surface Roughness (Ra) µm	S/N Ratio
1	300	2400	1	5.01	–14.0002
2	300	2600	2	5.24	–14.3866
3	300	2800	3	6.56	–16.3381
4	320	2400	2	5.26	–14.4197
5	320	2600	3	5.90	–15.4170
6	320	2800	1	6.59	–16.3777
7	340	2400	3	6.61	–16.4040
8	340	2600	1	5.80	–15.2686
9	340	2800	2	7.02	–16.9267

Table 17: S/N ratio response table of a 2 mm thickness of SPF-UPE composite cut with the AWJ cutting technique

Level	Water Pressure (MPa)	Traverse Speed (mm/min)	Stand-off-Distance (mm)
1	–14.91	–14.94	–15.22
2	–15.40	–15.02	–15.24
3	–16.20	–16.55	–16.05
Delta	1.29	1.61	0.84
Rank	2	1	3

The averages of the S/N ratio for the input processing parameters were estimated and illustrated in Figure 9 based on the responses of the average surface roughness in Table 19 for a material thickness of 4 mm. Similar to the case of 2 mm plate thickness, a blend of low levels of all of the input parameters produced the best surface roughness response. This result is consistent with what Sumesh *et al.* [47] and Prabu *et al.* [45] found, but in the current study, water pressure was the parameter that influenced the surface roughness the most, contrary to Prabu *et al.* [45], who found that the stand-off-distance was the most significant input affecting the surface roughness response. Based on the calculated max-min variance of the S/N ratio listed in Table 20, the significance of the variable input parameters was determined; the operating water pressure came first as the most influential input impacting the average of the surface roughness, whereas the nozzle traverse speed and stand-off-distance came second and third, respectively. According to the ANOVA calculations displayed in Table 21, the contributions of the inputs to the effect on the surface roughness response were 55.27% for water pressure, 34.43% for traverse speed, and 8.23% for stand-off-distance. A 300 MPa operating water pressure, 1800 mm/min nozzle traverse speed, and 1 mm stand-off-distance were recorded as the optimal

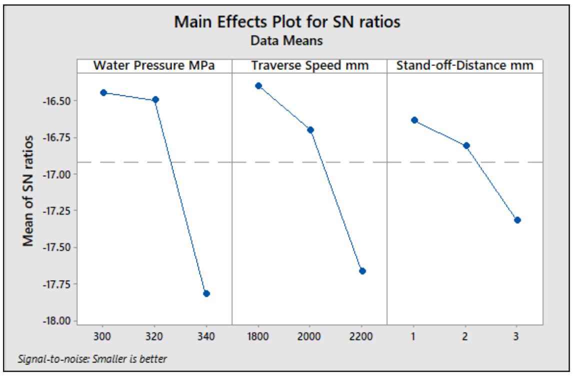

Figure 9: Average S/N ratio of the input cutting parameters of a 4 mm material thickness of SPF-UPE composite cut with the AWJ cutting technique

Table 18: ANOVA results for the surface roughness response of a 2 mm material thickness cut by the AWJ cutting technique

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	*F*-Value	*P*-Value
Water Pressure (MPa)	2	0.000990	28.63%	0.000990	0.000495	11.62	0.079
Traverse Speed (mm/min)	2	0.001819	52.62%	0.001819	0.000910	21.35	0.045
Stand-off-Distance (mm)	2	0.000563	16.28%	0.000563	0.000281	6.61	0.131
Error	2	0.000085	2.46%	0.000085	0.000043		
Total	8	0.003457	100.00%				

input processing parameters for the cutting of 4 mm specimen thickness of the SPF-UPE composite using the AWJ cutting technique regarding the desired response of the average surface roughness.

Table 19: Experiments' orthogonal array L9, measured surface roughness (Ra) and calculated signal-to-noise (S/N) ratio based on the Taguchi approach for a 4 mm plate thickness of SPF-UPE cut with the AWJ cutting technique

Ex no:	Water Pressure (MPa)	Traverse Speed (mm/min)	Stand-off-Distance (mm)	Average Surface Roughness (Ra) µm	S/N Ratio
1	300	1800	1	5.80	–15.2686
2	300	2000	2	6.46	–16.2047
3	300	2200	3	7.82	–17.8641
4	320	1800	2	6.41	–16.1372
5	320	2000	3	6.53	–16.2983
6	320	2200	1	7.12	–17.0496
7	340	1800	3	7.75	–17.7860
8	340	2000	1	7.58	–17.5934
9	340	2200	2	8.02	–18.0835

Table 20: S/N ratio response table of a 4 mm thickness of SPF-UPE composite cut with the AWJ cutting technique

Level	Water Pressure (MPa)	Traverse Speed (mm/min)	Stand-off-Distance (mm)
1	–16.45	–16.40	–16.64
2	–16.50	–16.70	–16.81
3	–17.82	–17.67	–17.32
Delta	1.38	1.27	0.68
Rank	1	2	3

Based on the estimated S/N ratio of the measured surface roughness displayed in Table 22 for the specimen with a 6 mm plate thickness, the average

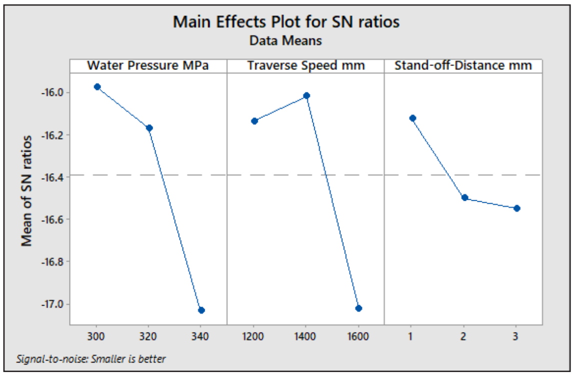

Figure 10: Average S/N ratio of the input cutting parameters of a 6 mm material thickness of SPF-UPE composite cut with the AWJ cutting technique.

values of the S/N ratio of all the input parameter levels are computed and illustrated in Figure 10. Under these operating conditions, the best response to the surface roughness was attained by applying a low level of water pressure, a medium traverse nozzle speed, and a low level of stand-off-distance. In Table 23, the levels of the effect of the input parameters on the surface roughness were computed by determining the max-min difference of the average S/N ratio. According to ANOVA data in Table 24, water pressure ranked first as the most effective factor on the surface roughness, with a contribution of 44.95%, whereas the traverse nozzle speed came second, with a contribution of 40.59%, and stand-off-distance did not exhibit a significant effect, with a contribution of 7.41%. Thus, 300 MPa water pressure, 1400 mm/min traverse speed, and 1 mm stand-off-distance produced the optimum response of the surface roughness for a 6 mm material thickness of SPF-UPE composite cut with AWJ cutting technology.

Table 21: ANOVA results for the surface roughness response of a 4 mm material thickness cut by the AWJ cutting technique

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	*F*-Value	*P*-Value
Water Pressure (MPa)	2	3.9776	55.27%	3.9776	1.98880	26.76	0.036
Traverse Speed (mm/min)	2	2.4779	34.43%	2.4779	1.23894	16.67	0.057
Stand-off-Distance (mm)	2	0.5924	8.23%	0.5924	0.29620	3.99	0.201
Error	2	0.1486	2.07%	0.1486	0.07431		
Total	8	7.1965	100.00%				

Table 22: Experiments' orthogonal array L9, measured surface roughness (Ra) and calculated signal-to-noise (S/N) ratio based on the Taguchi approach for a 6 mm plate thickness of SPF-UPE cut with the AWJ cutting technique

Ex no:	Water Pressure (MPa)	Traverse Speed (mm/min)	Stand-off-Distance (mm)	Average Surface Roughness (Ra) µm	S/N Ratio
1	300	1200	1	6.02	–15.5919
2	300	1400	2	5.92	–15.4464
3	300	1600	3	6.98	–16.8771
4	320	1200	2	6.41	–16.1372
5	320	1400	3	6.38	–16.0964
6	320	1600	1	6.51	–16.2716
7	340	1200	3	6.82	–16.6757
8	340	1400	1	6.69	–16.5085
9	340	1600	2	7.87	–17.9195

Table 23: S/N ratio response table of a 6 mm thickness of SPF-UPE composite cut with the AWJ cutting technique

Level	Water Pressure (MPa)	Traverse Speed (mm/min)	Stand-off-Distance (mm)
1	–15.97	–16.13	–16.12
2	–16.17	–16.02	–16.50
3	–17.03	–17.02	–16.55
Delta	1.06	1.01	0.43
Rank	1	2	3

Figure 11 displays the contributions of the input parameters to the effect on the surface roughness response of each plate thickness. In the case of a 2 mm material thickness, it was clear that every single input parameter had a considerable impact on the surface roughness response, as the nozzle traverse speed was the most important factor affecting the surface roughness response, and this is consistent with Dhakal *et al.* [49] and Jagadish *et al.* [30]; however, the importance of the traverse nozzle speed decreased in the cases of 4 mm and 6 mm plate thicknesses, to become the second most effective parameter in terms of influencing surface roughness. In general, the best surface roughness was obtained by applying the minimum levels of traverse speeds in all cases of material thicknesses except the experiment of a 6 mm material thickness, as the optimum surface roughness was obtained with the application of medium traverse speeds. For the cases of 4 and 6 mm plate thicknesses, the operating water pressure took the most important role in affecting the surface roughness, as the best response of surface roughness was achieved by applying low levels of water pressure. In 4 and 6 mm cases, it is also noticeable that the significance of the stand-off-distance decreased, as its contribution

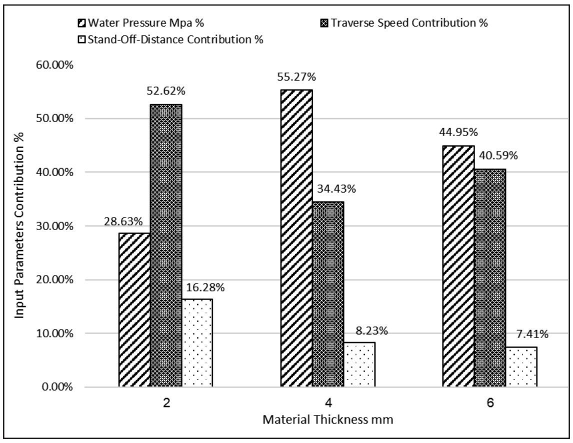

Figure 11: Input parameter contributions to the surface roughness of the different material thicknesses of SPF-UPE composite cut with the AWJ cutting technique.

Table 24: ANOVA results for the surface roughness response of a 6 mm material thickness cut by the AWJ cutting technique

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	*F*-Value	*P*-Value
Water Pressure (MPa)	2	0.000050	44.95%	0.000050	0.000025	6.38	0.136
Traverse Speed (mm/min)	2	0.000045	40.59%	0.000045	0.000023	5.76	0.148
Stand-off-Distance (mm)	2	0.000008	7.41%	0.000008	0.000004	1.05	0.487
Error	2	0.000008	7.05%	0.000008	0.000004		
Total	8	0.000112	100.00%				

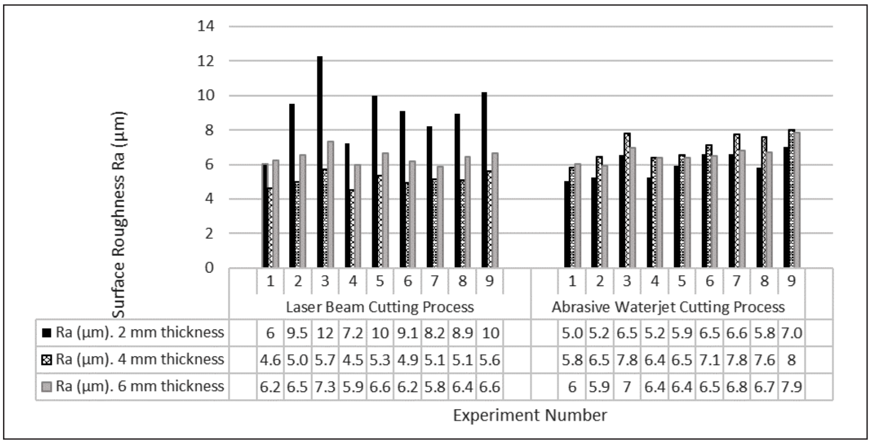

Figure 12: Surface roughness (Ra) relative to the experiment number and specimen thickness for abrasive AWJ and CO_2 laser cutting technique.

gradually decreased with the increase in the thickness of the material; this is in contrast to Prabu *et al.* [45], where the stand-off-distance represented the most important parameter in the cutting of banana fiber reinforced unsaturated polyester composite with the AWJ cutting technique. In general, the best response of surface roughness can be obtained by applying the minimum values of water pressures and traverse speeds in the range of parameter values tested in the current study. Furthermore, different values of the stand-off-distance, ranging from 1 to 3 mm, can be applied without expecting a significant effect, as the stand-off-distance factor did not show considerable importance, especially in the case of thicker specimens.

Both cutting techniques can be compared in terms of the surface roughness response and its effect on different material thicknesses. The surface roughness response of each experiment for both processes is illustrated in Figure 12. As shown in the figure, the higher values of surface roughness were recorded in the case of the thickness of 2 mm cut with the CO_2 laser cutting technique, as the surface roughness responses ranged from 6.01 to 12.3 µm, with an average of 9.05 µm. This can be explained as a result of the more effective thermal effect of the laser beam on the thinner specimens, especially given that the highest values of the surface roughness were recorded when applying higher traverse speeds, as there was not enough time for the assist gas to remove all of the decomposed material at the cutting kerf, producing rough cutting edges as a result of the remaining thermally decomposed material that was not been completely removed by the assist gas. In the rest of the experiments, the results were similar in both cutting processes, where the surface roughness values ranged from 4.5 to 7.3 µm in the cases of 4 and 6 mm material thicknesses cut using CO_2 laser cutting technology, while the surface roughness response ranged from 5.1 to 7.02 µm in the AWJ cutting process. It is clearly noticeable from Figure 12 that the material thickness has a significant effect in addition to the influence of the variation in the examined processing parameters in the cutting of the SPF-UPE composite with the CO_2 laser machining technique. In the abrasive water jet cutting process, the change in the material thickness did not exhibit a significant effect on the surface roughness response, while the most prominent effect was the variation in the tested processing parameters.

4 Conclusions

The AWJ and CO_2 laser cutting processes of SPF-UPE composite were successfully carried out. In both cutting processes, the measured values of the surface roughness were similar, except for the case of a 2 mm plate thickness cut with the CO_2 laser machining technique, which had significantly higher surface roughness values compared to the remainder of the material thicknesses in both cutting processes. The variation in the material thickness had a clear effect on the measured values of surface roughness in the case of the CO_2 laser cutting process, while the change in the material thickness did not show a significant impact on the surface roughness values in the AWJ cutting process. In the CO_2 laser cutting technique, traverse speed had the most significant effect on the surface roughness response in all cases of specimen thicknesses, followed by laser power and assist gas pressure, respectively, in the case of a 6 mm material thickness. In the cases of 2 and 4 mm specimen thicknesses, the traverse speed was still the most influential factor in terms of surface roughness response, followed by assist gas pressure and laser power, respectively. The input processing parameters that provided the optimum surface roughness values in the CO_2 laser machining technology were 150 mm/min cutting speed, 2 bar gas pressure, and 300 W laser power for a 2 mm material thickness. A 5600 mm/min traverse speed, 1300 W laser power, and 2 bar assist pressure were recorded as the best inputs for a 4 mm plate thickness cut with LBM cutting technique. The optimal processing parameters in the case of a 6 mm plate thickness were 7600 mm/min traverse speed, 2 bar assist pressure, and 2300 W laser power. In the AWJ machining technique, the nozzle traverse speed has the greatest influence on the surface roughness response, followed by the operating water pressure and stand-off-distance, respectively, and all of the input parameters had considerable contributions to the effect on surface roughness in the case of 2 mm material thicknesses. In the cases of 4 and 6 mm specimen thicknesses, the water pressure had the largest effect on the surface roughness, followed by the traverse speed, with relatively little contribution of the stand-off-distance. The optimum processing parameters that resulted in the desired response of the surface roughness in the AWJ cutting technique were a 2400 mm/min traverse nozzle speed, 300 MPa water pressure, and 1 mm stand-off-distance in the case of a 2 mm material thickness. For 4 mm specimen thickness, the optimum parameters were 300 MPa water pressure, 1800 mm/min traverse speed, and 1 mm stand-off-distance. The optimal parameters in the case of a 6 mm plate thickness were 300 MPa operating water pressure, 1400 mm/min traverse nozzle speed, and 1 mm stand-off-distance.

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Author Contributions

F.M. compiled and wrote the manuscript; S.M.S. supervised and reviewed the research; M.K.A.M.A. co-supervised; Y.N. co-supervised and provided data; E.B. was an international collaborator, who co-supervised, reviewed, and edited the paper. The published version of the manuscript has been read and approved by all authors.

Conflicts of Interest

The authors declare no conflict of interest.

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