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Performance Evaluation and MOORA Based Optimization of Pulse Width Control on Leather Specimens in Diode Laser Beam Cutting Process

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Abstract: Due to the variety of benefits over traditional cutting techniques, the usage of laser cutting technology has risen substantially in recent years. The attributes of laser technology for leather cutting include adaptability, mass production, capability of cutting complicated patterns, ease of producing tailored components, and reduction in leather waste. In the present study, vegetable chrome-tanned buffalo leather specimens were cut using a 20 W laser diode with conventional and pulse width control in a photodiode-assisted laser cutting process. Emission rate, kerf width, carbonization, and material removal rate were considered as quality indicators. The higher power density associated with the pulse width approach reduces the interaction with the specimen, which results in a better emission rate and material removal rate, along with a lesser kerf width and carbonization. Using the MOORA approach, the optimal parameters of the present study were found to be a stand-off distance of 22 mm, a feed rate of 200 mm/min, a duty cycle of 75%, and a frequency of 20 kHz. The duty cycle can effectively control the pulse width at which the energy has been dissipated across the cutting zone.

Keywords: leather; MOORA; carbonization; kerf; diode

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1. Introduction

Considerable attention is directed towards leather products due to their variety of applications (clothing, furniture upholstery, and automotive interiors). Leather has important applications in the aviation, automotive, and marine industries, where it is often used for seat covers and gaskets. Cow leather is one of the most widely available and used leathers, accounting for almost the majority of the market. When compared to cow leather, buffalo leather is known for having a smoother texture and higher durability [1,2]. Buffalo leather may range in thickness from 1.2 mm to 2.0 mm, depending on the manufacturer and the hide. This type of leather is highly valued for its strength and durability. Conventional leather cutting technologies include manual cutting, rotary cutting, and die pressing [3,4]. Conventional leather cutting techniques are slow and labor-intensive, which can be costly. Additionally, a lack was observed in the precision and accuracy of modern industrial cutting techniques [5,6]. Furthermore, conventional leather cutting tools require regular maintenance and sharpening, which can be time-consuming and costly. Due to their accuracy and efficiency, modern machining techniques, including water jet, laser, and electron beam machining, are becoming more popular for cutting leather [7]. These techniques are excellent for leather cutting since the processes can properly cut intricate forms and patterns [8].

Due to a variety of benefits over traditional cutting techniques, the usage of laser technology has risen substantially in recent times [9]. Laser cutting eliminates the need for

certain manual procedures. The advantages of laser cutting in leather include precision, accuracy, speed, and cost-efficiency [10]. Laser cutting allows for the creation of complex designs that are not possible with conventional methods of cutting. Additionally, it is more accurate and faster than traditional cutting methods, resulting in a more efficient production process [11]. Laser technology does not require contact with the material, which can reduce contamination risk and help maintain the integrity of the finished product. Due to its everlasting properties, laser technology has the ability to be utilized as a competing option for industry [12].

However, the depth of field generated by the laser depends on the type of laser, wavelength, and power intensity of the laser light beam [13]. The Heat Affected Zone (HAZ) is the portion that underwent laser ablation and has an unfavorable influence on the material design and structure. The existing system of non-conventional machining approaches, such as carbon dioxide (CO_2) gas laser-based laser beam machining (LBM) and two-axis diode LBM, has several drawbacks, including the creation of a large amount of carbonization. It has resulted in an undesirable finished product. The lack of a proper user interface for controlling and monitoring the machining process has to be rectified. The lack of automation should be reduced to optimize the input parameters accordingly [14]. Carbonization (CR) is a phenomenon that occurs when high temperatures are used to cut leather, causing the surface of the leather to become charred or blackened [15]. This process can damage the leather, reduce its strength, and result in an unpleasant smell.

The Laser Diode Assisted approach is highly economical as the machining time is small when compared with other conventional machining processes. Adaptive real-time monitoring and control is a technology that has been studied for a long time for its potential to automate laser cutting processes without human intervention [16,17]. Laser diode optical output power can be altered according to the workpiece through a controlled Pulse Width Modulation (PWM) signal.

However, its practical application has been hindered due to a lack of adequate sensors. The parametric analysis found that kerf width increases when process variables are set to a lower value while machining. Cutting metallic sheets using a laser medium is a well-established procedure. However, several new technologies and modifications in the process due to the introduction of new technologies have resulted in the need for considerably higher validation of the techniques being used [18,19]. The kerf width (KW) becomes minimal as the beam focus moves into the specimen of thick samples.

The Straightness of machine tool motion, the width of laser cuts, and the size of HAZ are used to evaluate laser cutting quality. A microscopic feature is also used to examine the surface of the defects [20,21]. Laser piercing necessitates continuous-wave or a high-duty cycle of more than 80% pulsed mode operation. Laser cutting using a high repetition rate, low power cycle pulsed mode laser achieved dross-free cuts with no distinct HAZ [22,23].

Statistical modeling and optimization are effective tools to study the effects of laser parameters on the surface roughness and the material removal rate of a workpiece [24]. As a result, the optimized parameters significantly improve the surface quality. The real-time velocity regulation strategy is an optimization algorithm that helps increase productivity in laser cutting. Many research studies have been conducted in the field of laser cutting to investigate the impact of machining parameters in diode-based LBM processes. Nevertheless, only a limited amount of literature is available on the implementation of control methodologies to improve the efficiency of machining [25]. Long-term research has been conducted on a technique known as adaptive real-time monitoring and control because of its potential to fully automate laser cutting procedures without requiring the participation of any humans [26]. On the other hand, its implementation in real-world settings has been hampered by a dearth of suitable sensors. The creation of photodiodes as a means of enhancing the productivity of laser cutting procedures. Photodiodes were utilized to detect the cutting process in real-time, which enabled a higher level of control and contributed to an improvement in productivity. Cutting machines that use laser technology are very cutting-edge pieces of machinery that can slice through a wide variety of materials

of varying densities and surface qualities in a single operation [27]. They come outfitted with highly developed process parameters as well as real-time monitoring and control systems that enable modifications to be performed. The end goal is to produce the highest possible cut quality with these machines. The traditional approach was not as accurate as the machine learning algorithm when it came to determining the roughness of the surface that had been sliced. This gives a helpful insight into the use of machine learning methods for the assessment of surface roughness seen in industrial settings. There are a variety of uses for LBM in a variety of sectors, including the automotive and aerospace industries, as well as the electrical, civil, and nuclear industries. Experimental investigations, modeling studies, and optimization experiments may be broken down into three distinct groups within LBM research. The experimental studies of LBM have shown that the process input parameters that impact process performance include cutting depth, optical power, cutting material shape and size, assist gas type, and mode of operation [28]. When the technology behind laser diodes advances and the process boundaries are stretched in order to meet the demands of metal sheet laser cutting, new obstacles present themselves. Because of the interaction between the laser and the nozzle tip, laser stream quality is a limiting factor that determines the nozzle diameter and the position of the focus point. In spite of the fact that it was anticipated that there would be a major loss in power at the nozzle corner, a significant gain in cutting speed was discovered. The efficiency of the machining process may be improved by increasing the laser power as well as the pulse frequency; however, increasing the scanning speed results in a reduction in the machining efficiency.

Due to the numerous characteristics of the cutting process, multi-criteria decision-making (MCDM) can be utilized in such research. The selection of the Grey coefficient is challenging in the Taguchi-Grey relational analysis (TGRA)-based MCDM approach [29]. Even though Taguchi-Data Envelopment Analysis-Based based Ranking(DEAR) is the simplest one, it cannot be applied to all lower-level performance measures [30]. The selection of weightage is a tedious one in the technique for order of preference by similarity to the ideal solution (TOPSIS)-assisted MCDM [31]. Even though a number of MCDM approaches are available to solve optimization problems, the Multi-Objective Optimization method based on Ratio Analysis (MOORA) is the most popular [32] due to its adaptability and prediction accuracy. From the extensive survey, it was found that only a few works have been available to compute the effects of the leather cutting process on environmental quality measures. In recent years, laser engraving on leather has become increasingly popular. The need for laser diodes for leather cutting has not been extensively explored. The effects of control algorithms in such cutting processes on leather specimens have to be explored further [33,34]. The MOORA-based MCDM approach in the lased-based leather-cutting process is only available in a limited quantity. Consequently, this endeavor was undertaken. In the present study, MOORA methodology was used to investigate the impact of laser power diodes under pulse width control on leather cutting quality measures. Section 2 contains the design of the laser cutting system, along with the design of experiments and optimization methodology. Section 3 explains the effects of pulse width control and process parameters on quality measures, along with multi-response optimization results.

2. Experimental Methodology

2.1. Design of Laser Cutting System

The entire laser cutting system (300 × 180 × 40 mm), including all the microcontroller units, transducer arrangements, driver circuits, motor actuators for rotation, and the laser diode module shown in Figure 1. As can be seen in Figure 1, a diode-based LBM experimental setup was conceptualized, built, and produced. In order to further adapt and improve the LBM system for leather cutting, the various parameter ranges at the input as well as the parameters at the output were taken into consideration. The arbitrary waveform generator model SGD 1010 and the ESP32 microcontroller were used in the production of the PWM signals. In this experiment, a mixed signal oscilloscope (MSO)

model number MSOX2004A was utilized to record pulse width modulated (PWM) signals that were produced for a three-axis laser beam machining system. There should be a minimum spacing of 10 mm between the laser focus point and the surface of the bed. A VL6180X Time of Flight (ToF) sensor has been included in the system in order to determine the distance, and an ESP32 microcontroller has been added in order to manage the pulse width modulation (PWM) of the laser module. In the current investigation, choosing the appropriate laser diode is an extremely important step. As a result of their ability to accurately cut and sculpt materials, blue diode lasers are well suited for use in cutting applications. Because leather has a high laser absorption coefficient, a blue laser diode with a wavelength of 450 nm has been selected for this study. There are three primary branches that make up the block representation of the diode LBM technique. The voltage input of 12 Volts and the current input of 2 Amperes are connected to the blue laser diode with an optical power of 5.5 Watts. The laser diode driver unit controls the laser irradiation. The standoff distance is determined by the Z-axis of the laser diode machining system, which is controlled by a stepper motor that is driven by the PSU. The quad-core Raspberry Pi 4 Model B, which incorporates all hardware and sensor systems, is then provided with power. It includes an LCD display offering touch interaction. The Open Builds CAM software comes pre-installed on this Raspberry Pi, allowing precise control at every stage. The open-source Arduino UNO microcontroller board based on the ATmega328P is then linked to the Raspberry Pi 4 Model B CPU used to drive the step motor-assisted vertical axis based on the distance detected by the ToF VL6180X sensor. There is no user-defined control approach in the existing LBM setup to cut leather in an optimal way. The comparative experiments have been conducted to obtain the optimal control loop approach and optimal parameters for leather cutting. The leather specimens were cut using a 20 W laser diode with an open-loop and a closed-loop mechanism. Figure 1(ii) shows the closed-loop PWM control.

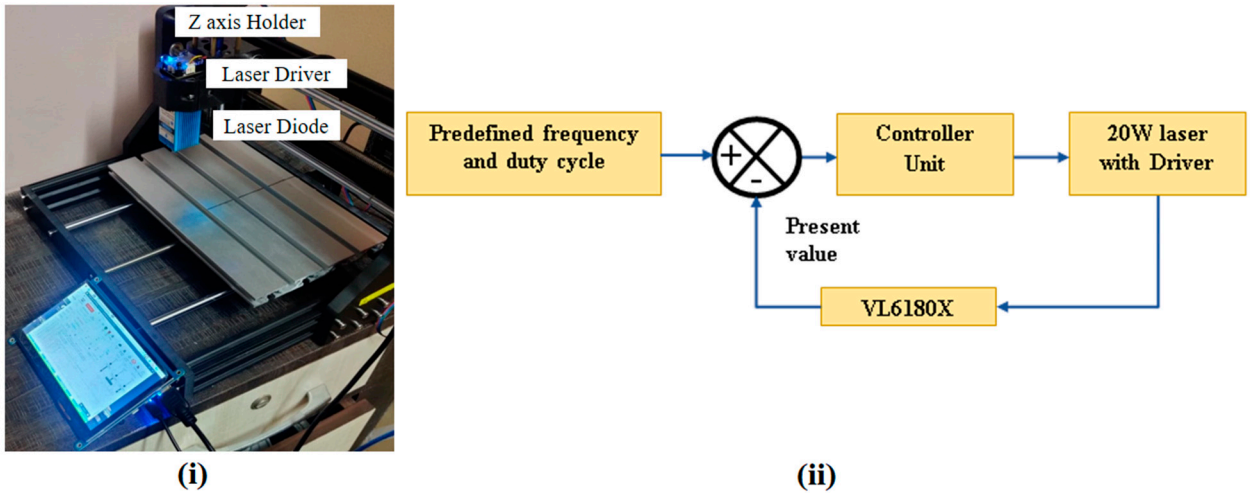


Figure 1. Laser cutting system (**i**) Complete laser diode cutting system (300 × 180 × 40 mm) (**ii**) Schematic representation of pulse width control.

The ESP32 microcontroller unit (MCU), Espressif Systems, Shanghai, China, has multiple frequency resolutions and two unique advantages. One of which is to control the duty cycle and frequency with respect to the thickness of the leather. The second is to reduce the manual setting of duty cycles and frequencies. The VL6180X time of flight (ToF), ST Microelectronics, Tsim Sha Tsui, Hong Kong, sensor is used to measure the thickness of the leather and feeds the data to the ESP32 to set the prescribed PWM parameters to perform a closed-loop control operation. As depicted in Figure 2, the percentage of carbonization was computed by determining the number of black-and-white pixels in the figure fetched after the incision. Using a binary threshold technique, the image was initially changed to grayscale before being covered in black and white [8]. An open-access python 3.11.4 software package called Open Computer Vision (Open CV) was used to program

the procedure. Figure 3 indicates the pulse width generated during the machining process, which has been captured using the Keysight mixed-signal Oscilloscope MSOX2004A with 70 MHz (Manufactured by Keysight, Santa Rosa, CA, USA). It was found that pulse width has been generated under 75% of the duty cycle. The duty cycle indicates the ratio between the pulse duration at which energy is applied and the total pulse duration. It means 3/4th pulse duration, at which the energy supplied for the cutting processes has an amplitude of around 5 V.

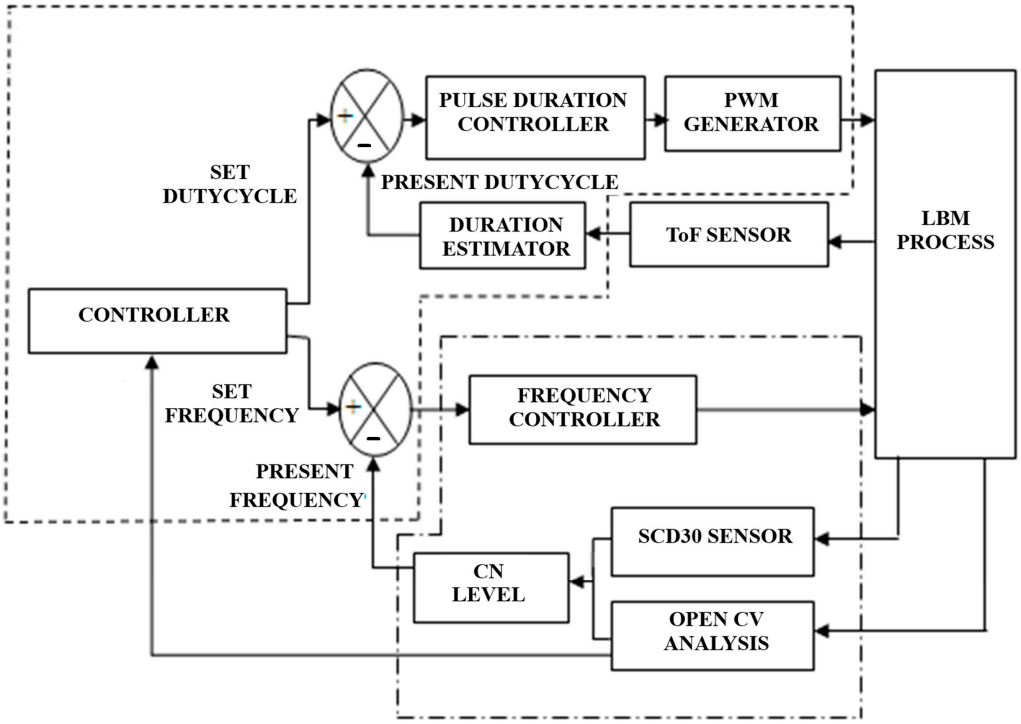


Figure 2. Control system block representation of modified controller.

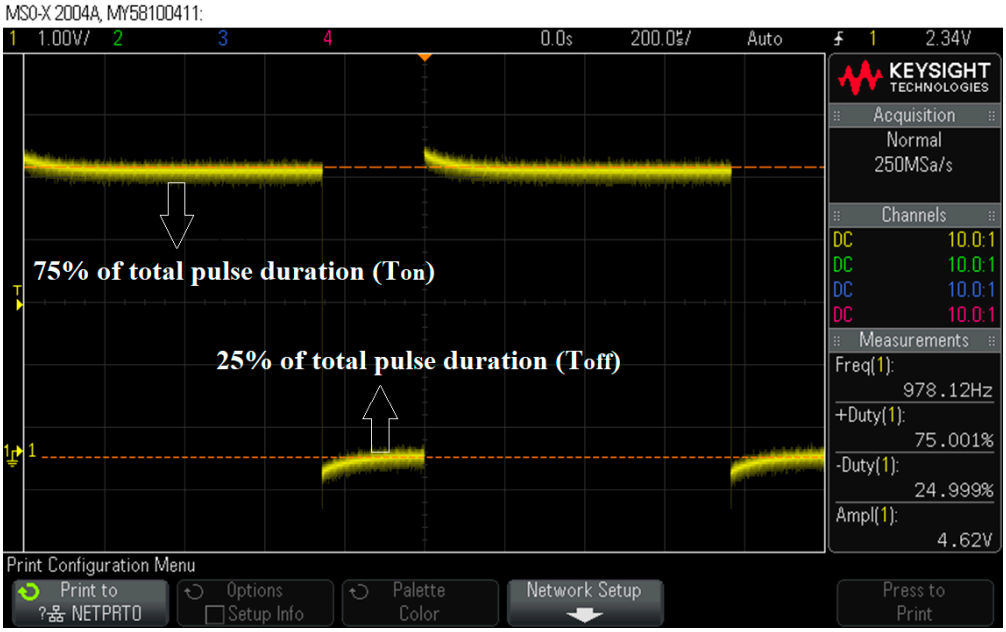


Figure 3. Pulse width control waveform with the duty cycle of 75% using MSO.

2.2. Selection of Leather Specimens

Chrome vegetable-tanned buffalo leather is made using a combination of vegetable and chrome tanning techniques. This process combines the strength and durability of chrome-tanned leather with the softness and flexibility of vegetable-tanned leather. It is also known for its superior strength, durability, and resistance to wear and tear, making it an ideal choice for many applications. Chrome vegetable-tanned buffalo leather of thickness 1 mm is used in the proposed study. It is also commonly used to create upholstery, clothing, saddles, automotive interior trim, and many other types of accessories.

2.3. Cutting Experimentation

The leather specimens were cut to create a 25-mm-diameter circle shape. The stand-off distance (SOD), duty cycle (DC), Feed rate (FR), and Frequency (F) were elected as the process input factors to assess the performance indicators. This study focuses on the implementation of self-tuned closed-loop control for the purpose of controlling the standoff distance in the laser-based machining process. The experiments have determined that a predefined standoff distance produces the best results. This parameter is maintained through the use of the self-tuned control closed loop. In this machining setup, the feed rate is an important factor for obtaining an accurate cut, and it was tested in the ranges shown in Table 1. DC is a measure of the amount of time a laser diode is in the ON mode when producing pulses. It was adjusted using pulse width modulation, which can be carried out with either an arbitrary waveform generator or an ESP32s PWM pin. Experiments were conducted using duty cycles of 70%, 75%, and 80% to examine the effects. The frequency of the laser diode module is the number of laser pulses that are being emitted from the laser per second. The laser has a maximum frequency of 20,000 Hz, and the ranges of 16,000 Hz, 18,000 Hz, and 20,000 Hz were considered to vary to obtain the results.

Table 1. Design of Experiments.

Trial No.	SOD (mm)	FR (mm/min)	DC (%)	F (KHz)
1	18	200	70	16
2	18	250	75	18
3	18	300	80	20
4	20	200	75	20
5	20	250	80	16
6	20	300	70	18
7	22	200	80	18
8	22	250	70	20
9	22	300	75	16

The emission rate (ER), carbonization (CN), Kerf width (KW), and material removal rate (MRR) were chosen as quality indicators in the present study. ER indicates the fumes are produced during the leather cutting process. Two SCD30 sensors measure the value of carbon in parts per million (ppm) during the machining process, one inside and one at the ECU-ZWAS [10]. As leather is a biomaterial, the contour margins of the machined leather generate carbon as a result of the pyrolysis process during laser ablation leather cutting. On leather margins, this procedure is known as carbonization. The percentage of carbonization was computed by determining the number of black-and-white pixels in the figure fetched after the incision. Using a binary threshold technique, the image was initially changed to grayscale before being covered in black and white [8]. An open-access

Python software package called Open Computer Vision (Open CV) was used to program the procedure. The percentage of CN was appraised by Equation (1).

$$\mathrm{CN}(\%) = \frac{\text{Pixels of black}}{\text{Pixels of black} + \text{Pixels of white}} * 100 \quad (1)$$

KW represents the overcut width created by laser material removal during machining. Equation (2) uses the MRR as an response factor to estimate the leather material removed per unit time.

$$\mathrm{MRR} = \frac{\text{specimen before cut} - \text{specimen after cut}}{\text{Time taken}} \mathrm{mg/s} \quad (2)$$

2.4. Taguchi—MOORA Methodology

As shown in Table 1, the L_9-based orthogonal array (OA) was considered for undertaking experimental tests in accordance with the Taguchi technique.

The process parameters were chosen after input from numerous leather manufacturers and laser machining specialists was considered. Because of their impact on productivity, the output variable percentages of ER, CN, KW, and MRR are considered output process parameters. Multi-response optimization (MRO) must be implemented because the traditional Taguchi design can only perform optimization for a single response. Due to its simplicity, the Taguchi—MOORA based MRO approach was utilized in the present investigation. For the optimization of parameters, the combination of recorded experimentation values is plotted as a ratio, and the subsequent steps are followed as shown in Figure 4 [26].

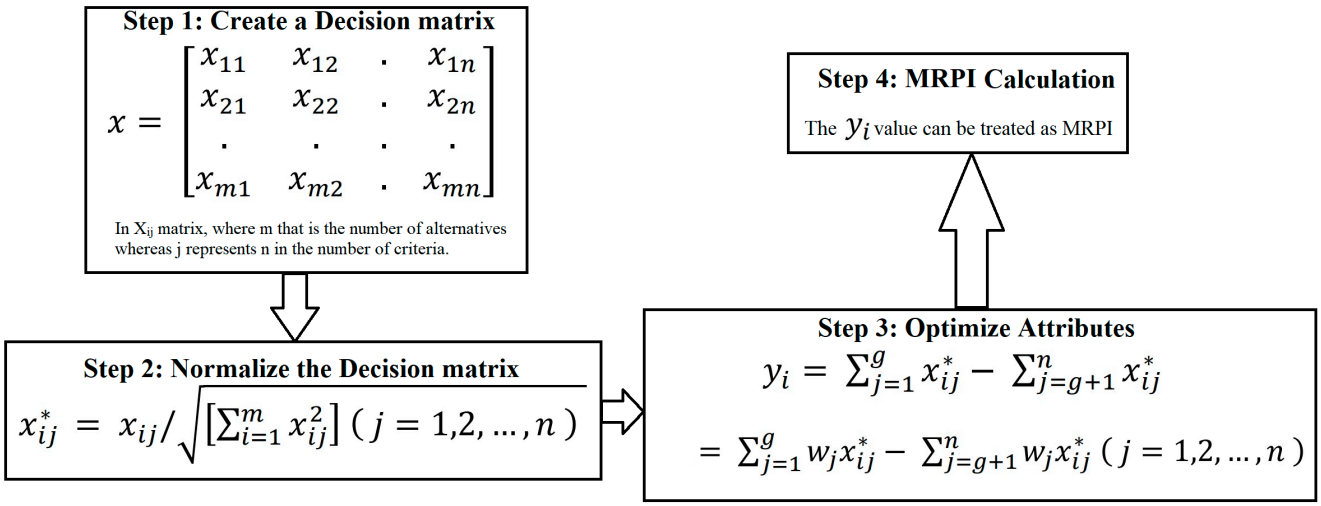


Figure 4. Technique to calculate MRPI using MOORA.

- The weights of each response were assumed.
- The assigned values were multiplied by their own responses to obtain the weighted values.
- The attributes were optimized to obtain the multiple performance performance index (MRPI). The various steps involved in calculating MRPI are shown in Figure 3.
- The mean values of quality measures were calculated.

3. Results and Discussion

The effects of pulse width-controlled diodes on quality metrics such as ER, CN, MRR, and KW are discussed. To improve the precision of the measurements, each experiment was repeated three times, and the mean was used as the final value. The numerous investigations were conducted in accordance with Table 2's experimental design.

Table 2. Experimental results.

Trial No.	ER		CN		KW		MRR	
	Without Control	Pulse Width Control	Without Control	Pulse Width Control	Without Control	Pulse Width Control	Without Control	Pulse Width Control
1	412.79	439.14	52.20	49.71	0.119	0.113	0.00722	0.007684
2	400.26	425.81	48.44	46.138	0.118	0.112	0.00716	0.007615
3	424.54	451.64	49.23	46.885	0.122	0.116	0.00738	0.00785
4	452.50	481.38	42.53	40.5	0.120	0.114	0.00755	0.008036
5	439.78	467.85	51.31	48.864	0.121	0.115	0.00750	0.007974
6	414.86	441.34	51.95	49.476	0.120	0.114	0.00732	0.007785
7	408.74	434.83	48.85	46.527	0.124	0.118	0.00768	0.00817
8	417.83	444.5	47.64	45.373	0.119	0.113	0.00751	0.007992
9	441.57	469.76	40.87	38.928	0.123	0.117	0.00740	0.007869

3.1. Effect of Pulse Width Control on Carbonization Performance Measures

It can be observed that instigating a closed control loop approach for PWM parameters reduces the kerf width while performing leather cutting. According to the above graphical representation, closed-loop PWM control is ideal for cutting leather. Since the combined control of PWM can control peak pulse energy and power density at the same time, it can produce lower kerfwidth as compared with other modes of control. Since the energy per pulse is determined by the pulse duration, the pulse width control can efficiently control the energy liberated during the cutting process as per Equations (3) and (4).

$$\text{Energy per pulse [J]} = \text{Average Power} * \text{Pulse duration} \tag{3}$$

$$\text{Average Power } (P_{avg})\,[\text{Watt}] = \frac{\text{Pulse Energy (E)}}{\text{Pulse Period } (\Delta t)} \tag{4}$$

When compared with a lower laser electrical power, a larger thermal energy may vaporize a greater quantity of leather material. Therefore, a greater amount of thermal energy has the potential to vaporize the substance in a more expedient way. On the other hand, it was discovered that increasing the cutting speed along with the laser power was able to create leather with a better surface quality while simultaneously reducing the impact of carbonization. The pulse width control of the diode laser allows for the diameter of the circular beam that it generates to be adjusted. The laser emits light in the form of a circle. As can be seen from Equations (3) and (4), the relationship between the pulse energy and the SOD is a direct one. The smaller the superoxide dismutase, the lower the peak pulse energy, and the less carbonization impact there will be. The length of time that the laser beam is focused on one location is determined by the "dwell time," which is an essential component of laser diode cutting. It has to be set so that it can produce a decent cut while also protecting the material from being subjected to an excessive amount of heat. Cutting leather with a laser diode is an efficient method that produces a nicer finish thanks to the elimination of striations during the cutting process. The laser beam that is created by a diode laser is more accurate and controlled than the laser beam that is produced by traditional techniques. This reduces the thermal effects and cutting force on the leather, resulting in a cut that is of superior quality. Because of its thermal action, laser cutting results in very little carbonization of the edge of the cut. In laser cutting, the pulse length is the most important parameter because it controls how long the material and the energy that is being fed into the workpiece spend interacting with one another.

3.2. Effect of Process Parameters on Quality Measures

Using the Minitab 17 software program, the main effects plot (MESP) was constructed in order to assess the impact that the various process parameters had on the quality measurements. A greater degree of deviation from the line indicating the horizontal mean suggests a greater degree of effect in cutting. The SOD and DC have a larger influence on quality measures such as ER, carbonization, KW, and MRR, as inferred from Figures 5–8 with pulse width control. In laser leather cutting, the MRR is also affected by the intensity of the laser diode. The laser intensity determines the amount of energy delivered to the leather, which affects the speed of cutting and the quality of the cut. The laser intensity is influenced by the flux, as indicated by Equation (5).

$$\text{Fluence}\left[\frac{\text{Joules}}{\text{cm}^2}\right] = \frac{\text{Average Pulse Energy [J]}}{\text{Focal spot area [cm}^2\text{]}} \quad (5)$$

A high-intensity laser beam can quickly vaporize the leather material, resulting in faster cutting speeds. However, excessively high laser intensity can also cause thermal damage to the leather, resulting in a rough or melted cut edge. To optimize the material removal rate in laser leather cutting, the laser intensity should be carefully controlled to balance cutting speed and cut quality. The optimal laser intensity may also depend on the thickness and type of leather being cut. In addition to laser intensity, the beam focus, the scan speed, and the pulse duration can also affect the material removal rate in laser leather cutting. It is important to optimize these parameters to achieve the desired cutting performance and minimize material waste. Since the kerf width is indirectly proportional to the feed rate, the lower FR can remove more material under high pulse energy to create a larger KW.

The interaction plot (IAP) was utilized to investigate the interactions among the process factors on quality measures. The cross-section of the responses mentioned by circle specifies the interactions among the process factors on quality measures. No interactions have been found among the quality measures except KW and MRR, as shown in Figures 9–12.

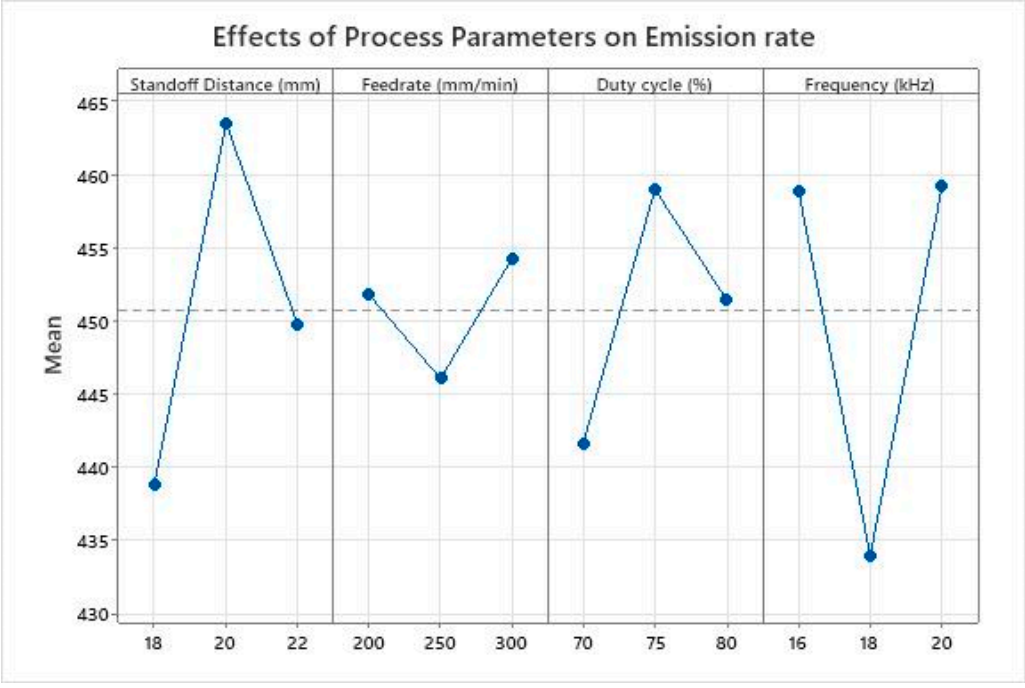


Figure 5. MESP of process factors on ER.

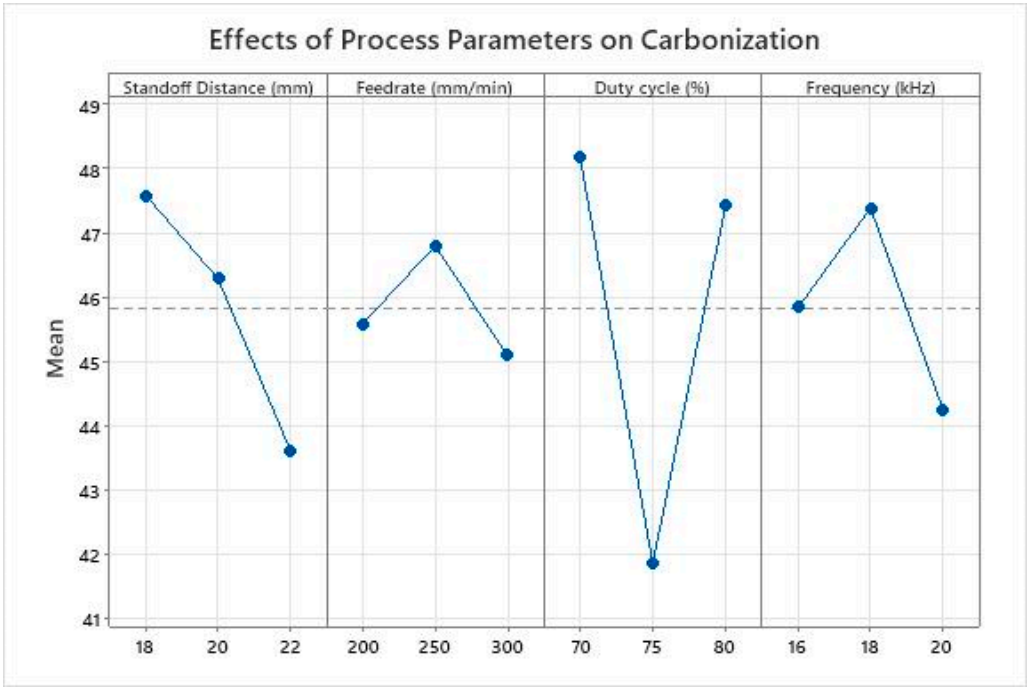


Figure 6. MESP of process factors on carbonization.

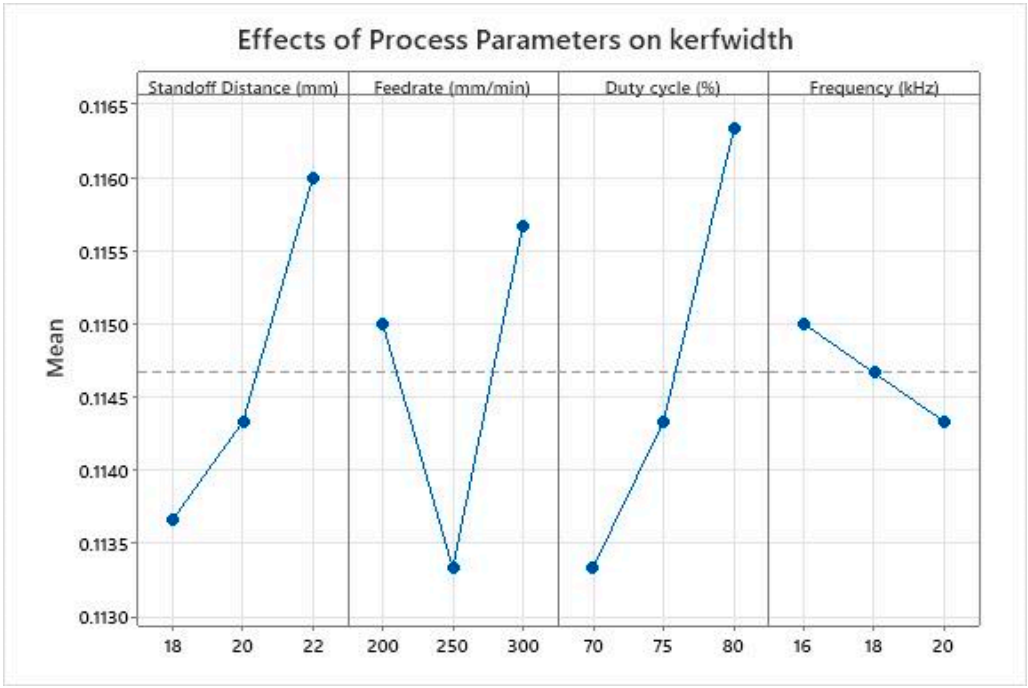


Figure 7. MESP of process factors on KW.

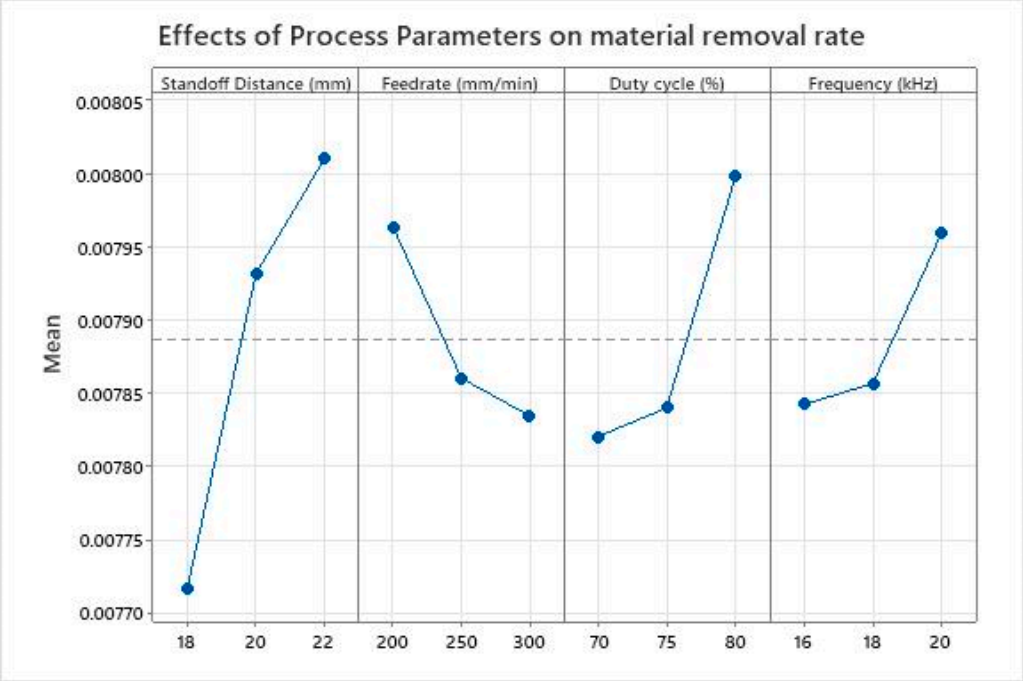


Figure 8. MESP of process factors on MRR.

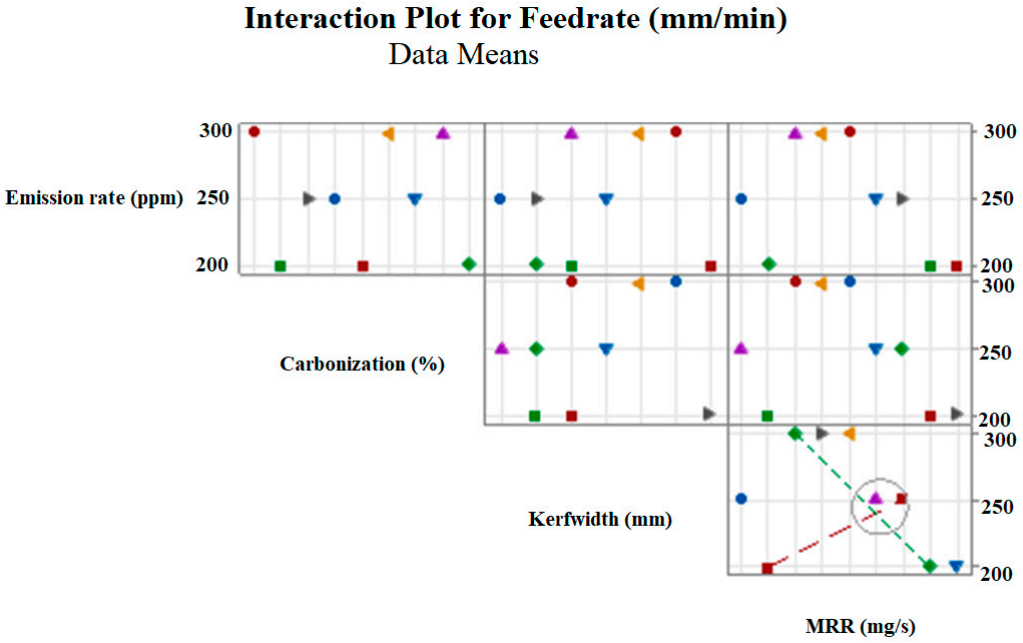


Figure 9. IAP plot for feedrate.

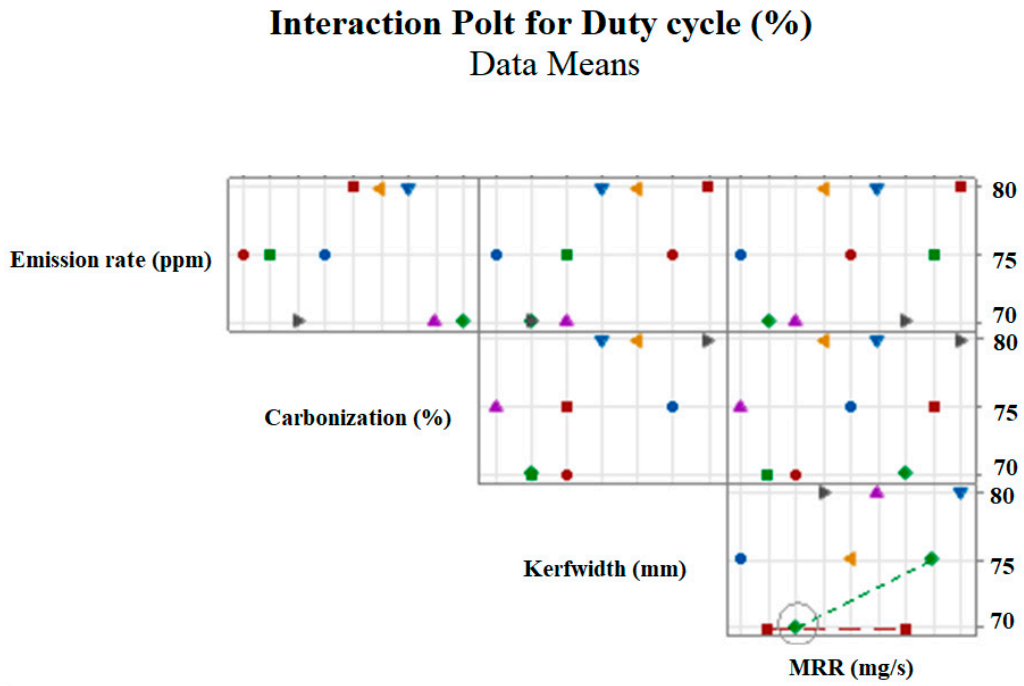


Figure 10. IAP plot for dutycycle.

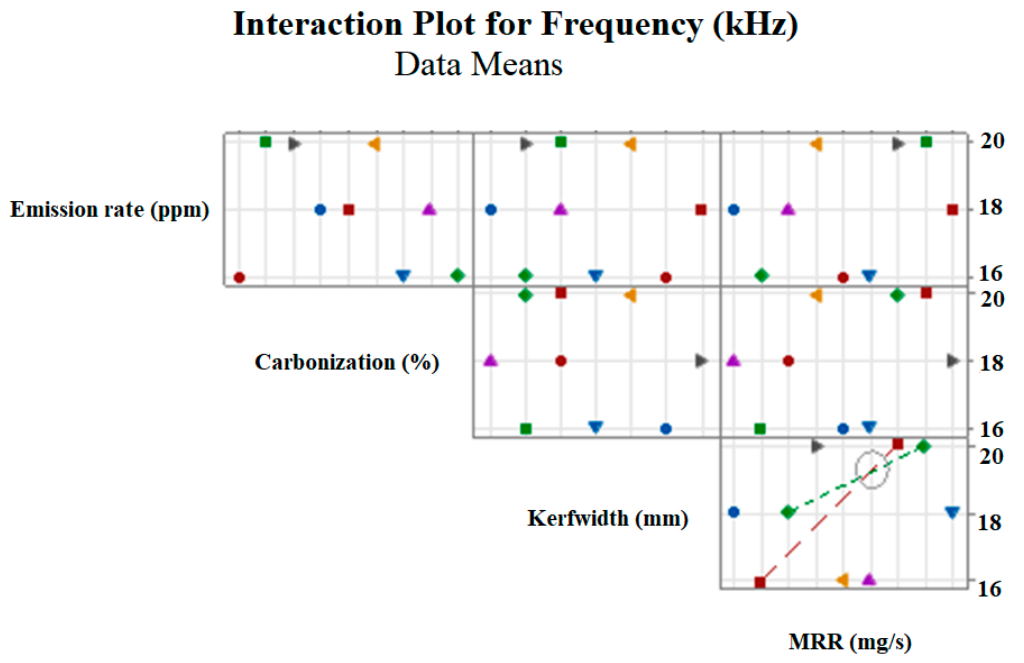


Figure 11. IAP plot for frequency.

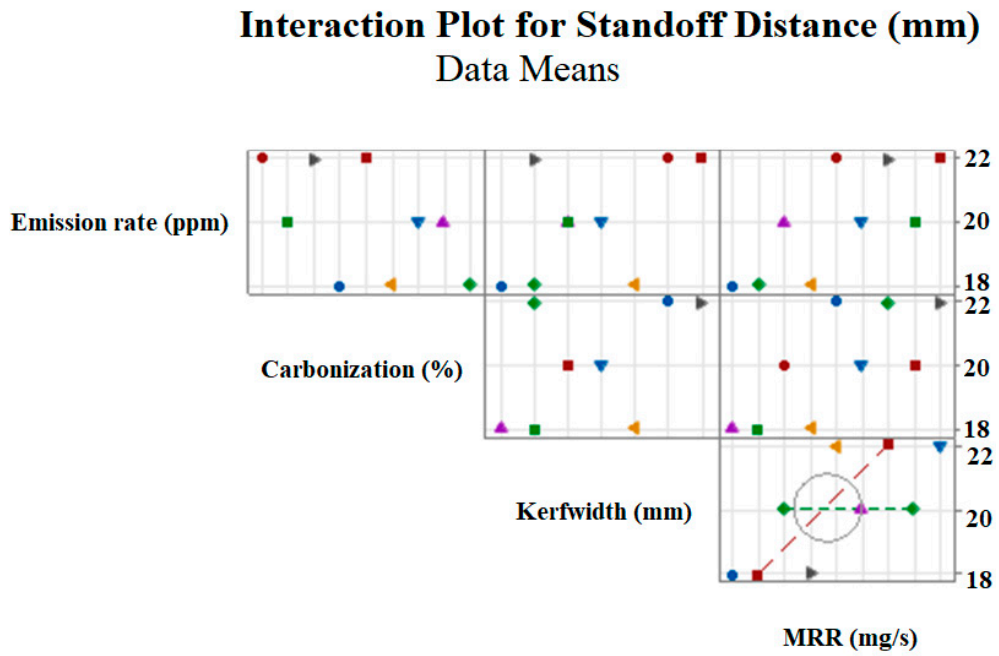


Figure 12. IAP plot for SOD.

3.3. Calculation of MOORA Based Optimal Parameters

Table 3 indicates the assignment of weights for the quality measures with pulse width control in the present study. The various quality measures, such as CN, KW, ER, and MRR, were considered with an equal weight of 0.25 for providing equal importance. Table 4 provides the weights of quality measures as calculated by the steps involved in Figure 4. The sign "+" indicates the larger the better response whereas "−" indicates the smaller the better response. The final single response can be analyzed using MRPI values. The MRPI values and rank were computed as shown in Table 5. Trial number 4 could provide optimal process parameters among the chosen combinations in the present study. Since the moderate values of SOD, FR, and DC at a higher frequency can efficiently control the pulse energy, trial 4 could produce better performance measures.

Table 5 indicates the optimal process parameters only among the nine chosen combinations of process factors. However, some other combinations other than the nine chosen can provide better quality measures. Table 6 indicates the computation of optimal parameter values by taking mean values under different parameter combinations in the present study. The larger value indicates the optimal combination of the factors in the process. Hence, it was found that SOD of 22 mm, FR of 200 mm/min, DC cycle of 75%, and F of 20 kHz were the optimal combination of process factors, as shown in Table 7. The larger max-min value recognizes the more influential factor. Therefore, it was found that DC has a more influential nature.

Table 3. Assignment of Weights.

Criteria	Description	Weightage
C1	Carbonization	0.25
C2	Kerf width	0.25
C3	Material removal rate	0.25
C4	Emission rate	0.25

Table 4. Calculations of weights of quality measures.

Trial Number	Weigths			
	ER (ppm)	Carbonization (%)	Kerf Width (mm)	MRR (mg/s)
1	0.0811	0.0901	0.0821	0.0812
2	0.0787	0.0837	0.0814	0.0804
3	0.0834	0.0850	0.0843	0.0829
4	0.0889	0.0734	0.0828	0.0849
5	0.0864	0.0886	0.0836	0.0842
6	0.0815	0.0897	0.0828	0.0822
7	0.0803	0.0844	0.0857	0.0863
8	0.0821	0.0823	0.0821	0.0844
9	0.0868	0.0706	0.0850	0.0831
Optimum	+	−	−	+

Table 5. Calculation of MRPI index and rank in this study.

Alternative	Maximum	Minimum	Y_i	Rank
1	0.1623	0.1722	−0.0099	9
2	0.1591	0.1650	−0.0059	7
3	0.1664	0.1693	−0.0029	5
4	0.1738	0.1563	0.0176	1
5	0.1707	0.1722	−0.0015	4
6	0.1638	0.1725	−0.0088	8
7	0.1667	0.1701	−0.0034	6
8	0.1666	0.1644	0.0022	3
9	0.1699	0.1556	0.0143	2

Table 6. Calculation of optimal factors.

Parameters	Levels			Max − Min
	1	2	3	
SOD	−0.0063	0.0024	0.0044	0.0106
FR	0.0014	−0.0017	0.0009	0.0031
DC	−0.0055	0.0087	−0.0026	0.0142
F	0.0010	−0.0060	0.0056	0.0116

Table 7. Computation of optimal parameter combination.

Parameters	Level	Values
SOD	3	22 mm
FR	1	200 mm/min
DC	2	75%
F	3	20 kHz

The DC indicates the pulse width at which the energy has been dissipated across the cutting zone. Since the present values are related to pulse width control, it can effectively enhance the quality measures. The same has been verified with MEP analysis on MRPI, as shown in Figure 13. The confirmation test was also performed with optimal factors obtained, as shown in Table 7. The quality measures were also calculated based on three experimental trials. It was found that the value has deviated only by 3.7%. Hence, the optimal factor combination was confirmed. In order to determine the surface topography of the machined specimen, a scanning electron microscope (SEM) was used with the appropriate combination of process parameters. As can be seen in Figure 14, the thickness and shape of the carbonization layer are both impacted by the manner in which radiant energy is distributed during the process of machining. As the duty cycle continues to go up, the intensity of the laser beam goes up as well, which causes a rise in the amount of heat produced. When subjected to such heat, the leather decomposes and then recombines. After the leather specimen has been machined with a diode laser, there will be some excess exertion caused by the CN layer of the machined leather. This layer may be wiped off using a cloth that has been dampened. After the diode laser cutting process, the machined specimen was forced to be evacuated so that the smell of a flame could be eliminated. During the process of cutting the leather, the laser diode cutting technique reduces the unwanted layer that is produced in the material. The process of machining also demonstrated that there was no taper formation at any point. On the machined surface's most exposed side, however, an unwelcome carbonization layer was discovered. This layer was seen on the surface's most exposed side.

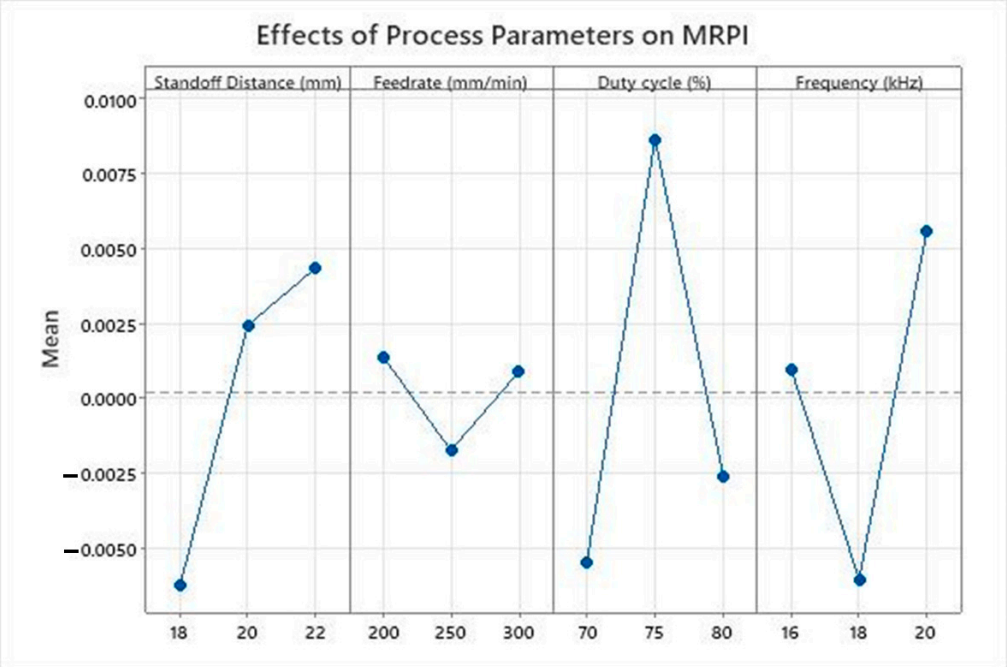


Figure 13. MEP of process factors on MRPI.

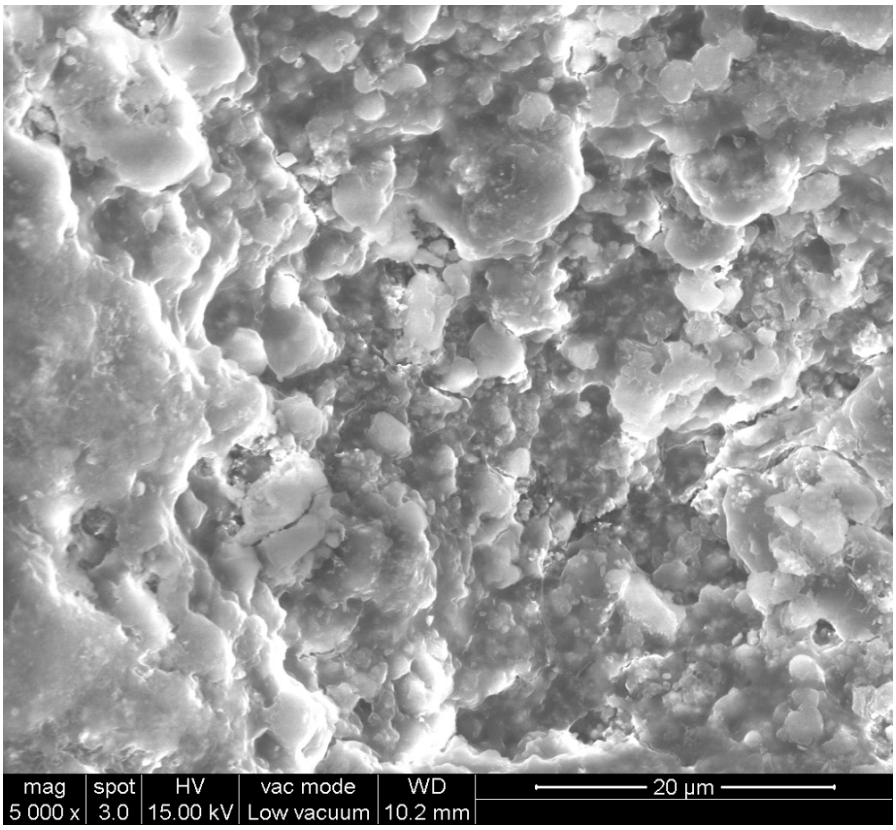


Figure 14. Cross section area of specimen using SEM based surface morphology.

The laser that is being used to produce the laser beam does not emit it in a vertical direction but rather has a scattering angle. Because a particular taper will be generated, the quality of the laser beam is also highly significant when cutting [10]. If you raise the speed of cutting, the KW will become narrower; however, if you lower the cutting speed, the KW will get wider. When the cutting speed is increased, the amount of dross that forms on the surface of the leather reduces. Additionally, when the cutting speed is increased, the surface quality of the machined leather improves. If the cutting speed is not fast enough, there will be a significant amount of dross formed in the kerf. When the cutting speed is increased beyond a certain point, there will be less dross formed in the kerf. However, if the speed of cutting is too high, it may be hard to penetrate the material. Because of this, it is very necessary to maintain control of the cutting speed and not aimlessly pursue high cutting speeds. Figure 15 shows the surface morphology of the leather specimen after the cutting process under optimal process parameter combinations. It was observed that lower dross formation had been observed over the leather specimens. Only a few striations have been found on the machined surface of the specimen [35]. The focus location has the greatest impact on the processing of a laser cutting machine, among the elements that have such an effect. The location of the focus will have an effect on the cutting factors, such as the width and the speed of the cutting. It is due to the fact that changing the focus position will cause the beam diameter on the surface of the material being processed to vary, as well as the incidence angle that will be introduced into the material being processed [36]. As a consequence of this, the formation state of the KW formation state will be altered, as will the many reflections of the beam that occur inside the kerf.

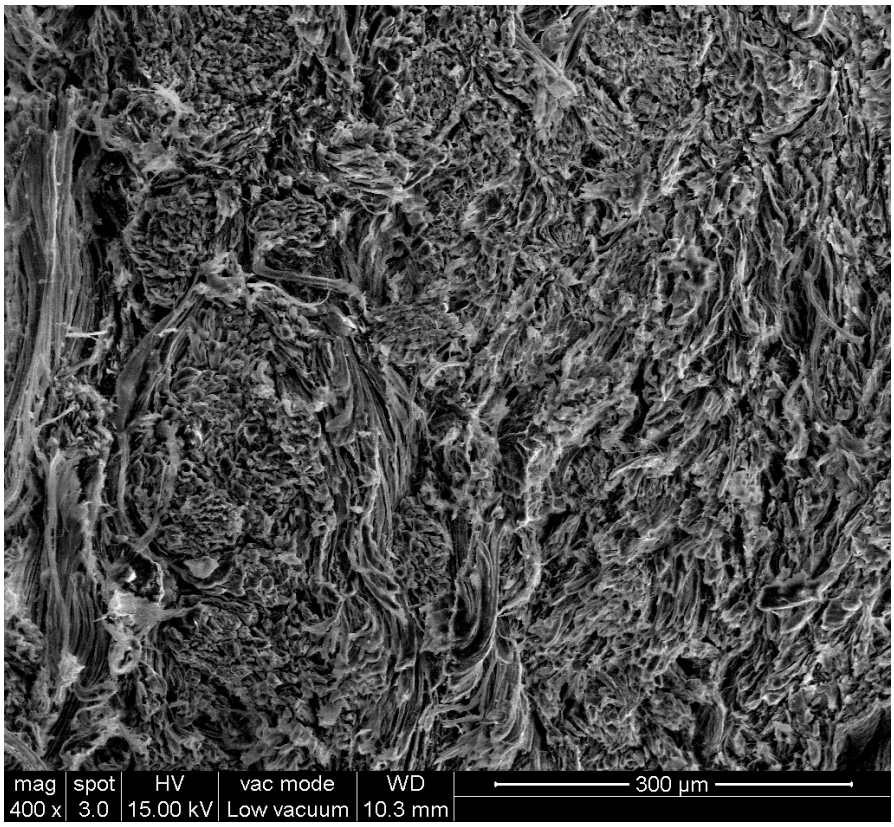


Figure 15. Surface morphology of machined leather specimen.

4. Conclusions

In the present work, an attempt was made to investigate the effects of pulse width control on performances such as CN, kerf width, material removal rate, and emission rate. The MOORA approach was also used to optimize the process factors. The following conclusions were drawn from the experimental analysis:

- Due to the ability to determine the energy per pulse by the pulse duration, the pulse width control can efficiently control the energy liberated during the cutting process to create enhanced quality measures.
- SOD and DC have a larger influence on quality measures such as ER, carbonization, KW, and MRR under pulse width control owing to control over average pulse energy.
- The optimal parameters are found to be an SOD of 22 mm, a FR of 200 mm/min, a duty cycle of 75%, and a frequency of 20 kHz with an error of 3.7%.
- Since the duty cycle can effectively control the pulse width at which the energy has been dissipated across the cutting zone, it has higher influential role in the process.
- Since power diode-assisted laser cutting is a material removal mechanism, the combining of the laser beam can be performed. Further research can be performed using coherent beam combining and spectral beam combining to increase the overall source brightness.

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References

1. Stepanov, A.; Manninen, M.; Parnanen, I.; Hirvimaki, M.; Salminen, A. Laser cutting of leather: Tool for industry or designers? *Phys. Procedia* **2015**, *78*, 157–162. [CrossRef]
2. Alves, C.; Bras, P.; de Carvalho, J.V.; Pinto, T. New constructive algorithms for leather nesting in the automotive industry. *Comput. Oper. Res.* **2012**, *39*, 1487–1505. [CrossRef]
3. Caiazzo, F.; Curcio, F.; Daurelio, G.; Minutolo, F.M.C. Laser cutting of different polymeric plastics (PE, PP and PC) by a CO_2 laser beam. *J. Mater. Process. Technol.* **2015**, *159*, 279–285. [CrossRef]
4. Wu, C.; Li, M.; Huang, Y.; Rong, Y. Cutting of polyethylene terephthalate (PET) film by 355 nm nanosecond laser. *Opt. Laser Technol.* **2021**, *133*, 106565. [CrossRef]
5. Nasim, H.; Jamil, Y. Diode lasers: From laboratory to industry. *Opt. Laser Technol.* **2014**, *56*, 211–222. [CrossRef]
6. Gisario, A.; Boschetto, A.; Veniali, F. Surface transformation of AISI 304 stainless steel by high power diode laser. *Opt Lasers Eng.* **2011**, *49*, 41–51. [CrossRef]
7. Liu, S.; Thangamani, G.; Thangaraj, M.; Karmiris-Obratański, P. Recent trends on electro chemical machining process of metallic materials: A review. *Archiv.Civ.Mech.Eng* **2023**, *23*, 158. [CrossRef]
8. Vasanth, S.; Muthuramalingam, T. Application of laser power diode on leather cutting and optimization for better environmental quality measures. *Archiv. Civ. Mech. Eng.* **2021**, *21*, 54. [CrossRef]
9. Filho, E.Q.S.; Sousa, P.H.F.D.; Filho, P.P.R.; Barreto, G.A.; Albuquerque, V.H.C.D. Evaluation of Goat Leather Quality Based on Computational Vision Techniques. *Circuits Syst. Signal Process.* **2020**, *392*, 651–667. [CrossRef]
10. Vasanth, S.; Muthuramalingam, T. Measurement of carbonization region on leather cutting in CO_2 and diode laser-based laser beam process. *Proc. Inst. Mech. Eng. E J. Process Mech. Eng.* **2022**, *236*, 1076–1082. [CrossRef]
11. Muttaqien, A.T.; Erwanto, Y.; Rohman, A. Determination of buffalo and pig rambak crackers using FTIR spectroscopy and chemometrics. *Asian J. Anim. Sci.* **2016**, *10*, 49–58. [CrossRef]
12. Varghese, A.; Jain, S.; Prince, A.M.; Jawahar, M. Digital microscope image sensing and processing for leather species identification. *IEEE Sens. J.* **2020**, *20*, 10045–10056. [CrossRef]
13. Muthuramalingam, T.; Moiduddin, K.; Akash, R.; Krishnan, S.; Mian, S.H.; Ameen, W.; Alkhalefah, H. Influence of process parameters on dimensional accuracy of machined Titanium (Ti-6Al-4V) alloy in Laser Beam Machining Process. *Opt. Laser. Technol.* **2020**, *132*, 106494. [CrossRef]
14. Junaid, M.; Malik, R.N.; Pei, D.S. Health hazards of child labor in the leather products and surgical instrument manufacturing industries of Sialkot, Pakistan. *Environ. Pollut.* **2017**, *226*, 198–211. [CrossRef]
15. Sarkar, T.; Salauddin, M.; Hazra, S.K.; Chakraborty, R. Effect of cutting edge drying technology on the physicochemical and bioactive components of mango (Langra variety) leather. *J. Agric. Food Res.* **2020**, *2*, 100074. [CrossRef]
16. Lee, J.; Hong, J.; Jang, D.; Park, K.Y. Hydrothermal carbonization of waste from leather processing and feasibility of produced hydrochar as an alternative solid fuel. *J. Environ. Manag.* **2019**, *247*, 115–120. [CrossRef] [PubMed]
17. Sathish, M.; Madhan, B.; Rao, J.R. Leather solid waste: An eco-benign raw material for leather chemical preparation–A circular economy example. *Waste. Manag.* **2019**, *87*, 357–367. [CrossRef]
18. Muthuramalingam, T.; Akash, R.; Krishnan, S.; Phan, N.H.; Pi, V.N.; Elsheikh, A.H. Surface quality measures analysis and optimization on machining titanium alloy using CO2 based Laser beam drilling process. *J. Manuf. Process.* **2021**, *62*, 1–6. [CrossRef]
19. Rodrigues, G.C.; Vanhove, H.; Duflou, J.R. Direct diode lasers for industrial laser cutting: A performance comparison with conventional fiber and CO_2 technologies. *Phys. Procedia* **2014**, *56*, 901–908. [CrossRef]
20. Rodrigues, G.C.; Cuypers, M.; Sichani, E.F.; Kellens, K.; Duflou, J.R. Laser cutting with direct diode laser. *Phys. Procedia* **2013**, *41*, 558–565. [CrossRef]
21. Sakaev, I.; Ishaaya, A.A. Diode laser assisted oxygen cutting of thick mild steel with off-axis beam delivery. *Opt. Laser Technol.* **2021**, *138*, 106876. [CrossRef]
22. Wang, Z.; Li, T.; Yang, G.; Song, Y. High power, high efficiency continuous wave 808nm laser diode arrays. *Opt. Laser Technol.* **2017**, *97*, 297–301. [CrossRef]
23. Vasanth, S.; Muthuramalingam, T.; Prakash, S.S.; Raghav, S.S. Investigation of SOD control on leather carbonization in diode laser cutting. *Mater. Manuf. Process.* **2022**, *38*, 544–553. [CrossRef]
24. Kanagaraj, J.; Panda, R.C.; Kumar, M.V. Trends and advancements in sustainable leather processing: Future directions and challenges–A review. *J. Environ. Chem. Eng.* **2020**, *8*, 104379.

25. Tatzel, L.; Tamimi, O.A.; Haueise, T.; Leon, F.P. Image-based modelling and visualization of the relationship between laser-cut edge and process parameters. *Opt. Laser Technol.* **2021**, *141*, 107028. [CrossRef]
26. Phillips, T.; Ricker, T.; Fish, S.; Beaman, J. Design of a laser control system with continuously variable power and its application in additive manufacturing. *Addit. Manuf.* **2020**, *34*, 101173. [CrossRef]
27. Biswas, S.; Mandal, K.; Roy, N.; Biswas, R.; Kuar, A.S. Study on kerf width deviation of microchannel with various medium in laser transmission cutting by diode pump fiber laser. *Mater. Today* **2020**, *26*, 804–807. [CrossRef]
28. Alsoruji, G.; Muthuramalingam, T.; Moustafa, E.B.; Elsheikh, A.; Muthuramalingam, T. Investigation and TGRA based optimization of laser beam drilling process during machining of Nickel Inconel 718 alloy. *J. Mater. Res. Technol.* **2022**, *18*, 720–730. [CrossRef]
29. Muthuramalingam, T. Effect of diluted dielectric medium on spark energy in green EDM process using TGRA approach. *J. Clean. Prod.* **2019**, *238*, 117894. [CrossRef]
30. Thangaraj, M.; Ahmadein, M.; Alsaleh, N.A.; Elsheikh, A.H. Optimization of Abrasive Water Jet Machining of SiC Reinforced Aluminum Alloy Based Metal Matrix Composites Using Taguchi–DEAR Technique. *Materials* **2021**, *14*, 6250. [CrossRef]
31. Phan, N.H.; Muthuramalingam, T. Multi-criteria Decision-making of Vibration-aided Machining for High Silicon-carbon Tool Steel with Taguchi–topsis Approach. *Silicon* **2021**, *13*, 2771–2783. [CrossRef]
32. Muthuramalingam, T.; Sakthivel, G.; Saravanakumar, D. Application of failure mode and effects analysis in manufacturing industry- an integrated approach with FAHP–FUZZY TOPSIS and FAHP-FUZZY VIKOR. *Int. J. Product. Qual. Manag.* **2018**, *24*, 398–423.
33. Vasanth, S.; Muthuramalingam, T.; Prakash, S.S.; Raghav, S.S.; Logeshwaran, G. Experimental investigation of PWM laser standoff distance control for power diode based LBM. *Opt. Laser Technol.* **2023**, *158*, 108916. [CrossRef]
34. Vasanth, S.; Muthuramalingam, T.; Prakash, S.S.; Raghav, S.S.; Logeshwaran, G. Implementation and performance analysis of combined SOD and PWM control in diode based laser beam machining process on leather specimen. *Opt. Laser Technol.* **2024**, *169*, 110093. [CrossRef]
35. Wang, L.; Yin, K.; Deng, Q.; Huang, Q.; He, J.; Duan, J. Wetting Ridge-Guided Directional Water Self-Transport. *Adv. Sci.* **2022**, *9*, 2204891. [CrossRef]
36. Swaminathan, V.; Thangaraj, M.; George Joseph, E.; Sulfikar Khadar, S.; Philip Saji, J.; Karmiris-Obratański, P. Analysis of Carbon Formation on Machined Leather Specimen Using FTIR Technique in Laser Diode Assisted Cutting Process. *Materials* **2023**, *16*, 148. [CrossRef]

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