Parameter Optimization for CO\(_2\) Laser Cutting of Wood Polymer Composite (WPC)

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Abstract. Wood polymer composites (WPC) are being used widely in various industries due to its wood-like appearance and durability which makes it a suitable substitute for wood in internal decorations. This study involves cutting the WPC (20% wood) of 8mm thickness using CO\(_2\) laser cutting machine and the best parameter is obtained in order to get the best cut. The laser cutting machine used in this experiment has a power rating of 50W and the experimental procedures involves variable power setting from 60\% - 80\%. The nozzle height was also varied ranging from 4mm to 6mm and the cutting speed from 2 – 4 mm/s. The cut material was analysed by taking the reading of top kerf width. The best parameter is then used to cut decorative wood panels which imitate traditional Malay wood carvings (papan pemanis) to be installed at homes. Through the analysis, there are total 10 solutions being generated which will produce good cut quality.

1. Introduction
This study was done to adapt a new technology for an old tradition of wood carving which has been a very popular internal and external house decoration (papan pemanis) [1] as shown in Figure 1. Previously, pure wood blocks carved manually by skilled craftsmen were used to make repetitive designs which will be then installed on walls or railings. The idea of this study is to replace traditional wood blocks with wood polymer composites (WPC) and it would be machined using a CO\(_2\) laser cutting machine.

There are many previous studies [2] which mentions about CO\(_2\) laser cutting and its parameter optimization and therefore those techniques can be adopted to study the process parameter of cutting WPC using CO\(_2\) laser cutting machine. The most common parameters studied are nozzle design, variations in shield gas velocity, cutting speed, type of shield gas and focal configuration [2].
2. Methodology
The total number of parameters usually being studied for laser cutting varies across different research and this can be limited due to available resources. For this study, only three factors are taken into consideration, which are laser power, cutting speed and nozzle height. The technique used for this experiment has been adopted from previous researches which studies individual effects and also explores the relationship between several variable factors and this technique is called response surface method (RSM). It uses statistical analysis to deduce the optimum values of factors to get the best response according to requirement.

2.1. Laser cutting parameters
Laser cutting technology has been developing to cater for various industries because of its efficiency and user friendly mechanism. It is being used to cut from metals as well as timber materials like medium density fibreboard (MDF) [2]. When a different industry adopts this machining technique, proper attention would be given to the laser cutting parameters and this further extends the usage of laser cutting machining. Previous studies have identified importance of process parameters like laser power, cutting speed, and shield gas to determine the cut quality for different materials [3]. Other than that, the nozzle design and the shield gas velocity can also be an important factor for certain materials like MDF. There are also some advanced factors that should be looked on for intricate details like beam spot diameter, thermal conductivity, reflectivity of workpiece material and interactions between various factors [5]. However, in this study, we would be focusing only on laser power, cutting speed and nozzle height.

2.1.1. Laser power. Laser power has direct effect on the surface quality due to the extreme heat produced while machining. One of the functions of assist gas is to remove the molten material before solidification takes place but this has to work simultaneously with suitable laser power. Previous studies has shown that the surface roughness generally increases with higher laser power [3, 6]. Improper setting of laser power would also increase the kerf width, cause a larger hole diameter as well as more irregular striation lines.

2.1.2. Cutting speed. For a given thickness of material, there would be a range of cutting speed including an optimum value based on cut quality. Cutting speed is also an important economic variable as a higher cutting speed would deduce a lower cycle time and therefore reduce the unit cost. It is shown that the energy loss at the cut zone can be decreased with an increase in the cutting speed, resulting in a more efficient process [3]. Similarly, when a thicker material is to be cut, the cutting speed has to be reduced, causing more energy to be wasted at the cut zone. The levels of thermal energy loss from the cut zone in most cases, rises rapidly with increasing material thickness coupled with the reduction in cutting speed [7].

2.1.3. Nozzle height. Many types of nozzle design has actually been adapted from industries that involves gas dynamics. A proper nozzle design has to provide a shock-free flow as well as ease of manufacturing. There are nozzles which have shaped contracting part and a smooth throat part that can...
produce a completely shock-free flow, but are impractical because of their high cost as no mass manufacturing technique exist as of the year 2008 [6]. Nozzle height is also important as an inappropriate height will cause formation of burr towards the lower part of the workpiece [8].

2.2. Material
Wood polymer composite (WPC) is a relatively new product being used extensively compared to commercial wood and timber in various industries [9]. WPC proves to be a better alternative as it is more environmental friendly and requires lesser maintenance. This quality has caused a demand for companies that specializes in manufacturing WPC for home application. WPC is made by mixing ground wood particles with selective thermoplastic resin and then extruded to produce end product with desired dimension and design. The main objective of this study is to produce ‘papan pemanis’, a traditional wood ornament using WPC and being machined using CO$_2$ laser cutting machine.

2.3. Design of experiment
The design of experiment used for this experiment was central composite design with alpha 1 and face-centered. Through this DOE there were total 20 number of runs due to 3 variable factors and 1 individual response. Table 1 shows the factors and response affiliated with experimental terms.

| No | Statistical term | Experimental term | Levels |
|----|------------------|--------------------|-------|
| 1  | Factor A         | Laser power (%)    | -1    |
| 2  | Factor B         | Cutting speed (mm/s)| 0     |
| 3  | Factor C         | Nozzle height (mm) | +1    |
| 4  | Response         | Top kerf width     |       |

3. Results and Discussion
All the data that were recorded after the cutting process were recorded in a table before analysis using a statistical software in a method called response surface method (RSM). The analysis involved the study of relationship among various parameters, namely cutting speed, laser power and nozzle height. The relation between individual parameter with the cutting quality were initially studied before obtaining the joined relation of multiple parameters with cutting quality. All the raw data were initially included in Table 2 before proceeding with data analysis.

Table 2: Data extracted after 20 runs using CO$_2$ laser cutting machine

| Runs | Factor A | Factor B | Factor C | Response |
|------|----------|----------|----------|----------|
| 1    | 60       | 2.00     | 6.00     | 1.269    |
| 2    | 70       | 3.00     | 5.00     | 0.699    |
| 3    | 80       | 4.00     | 4.00     | 1.048    |
| 4    | 80       | 3.00     | 5.00     | 0.689    |
| 5    | 70       | 3.00     | 5.00     | 0.813    |
| 6    | 80       | 4.00     | 6.00     | 1.111    |
| 7    | 70       | 3.00     | 5.00     | 0.855    |
| 8    | 70       | 3.00     | 5.00     | 0.615    |
| 9    | 70       | 3.00     | 4.00     | 0.665    |
| 10   | 60       | 4.00     | 6.00     | 0.715    |

| Runs | Factor A | Factor B | Factor C | Response |
|------|----------|----------|----------|----------|
| 11   | 70       | 4.00     | 5.00     | 1.121    |
| 12   | 60       | 2.00     | 4.00     | 1.352    |
| 13   | 80       | 2.00     | 6.00     | 1.502    |
| 14   | 70       | 3.00     | 5.00     | 0.653    |
| 15   | 70       | 3.00     | 6.00     | 0.818    |
| 16   | 70       | 2.00     | 5.00     | 1.441    |
| 17   | 80       | 2.00     | 4.00     | 1.460    |
| 18   | 60       | 3.00     | 5.00     | 0.504    |
| 19   | 60       | 4.00     | 4.00     | 0.720    |
| 20   | 70       | 3.00     | 5.00     | 0.727    |
3.1. Analysis

For the beginning, from the fit summary analysis, the suggested highest order polynomial is quadratic. Next step is the analysis of variance (ANOVA), from which we can see the linear and quadratic effect of each factors involved in this experiment. Through this analysis, we can also identify if the factors are significant for the response or not by looking at the P value. Any value below 0.05 is considered to be significant and vice versa. However only the significant factors will be used in the general equation by the end of this analysis as the factors which are not significant does not have much effect on the response generally. Figure 2 shows the revised ANOVA table without the factors which are not significant.

![Figure 2: Revised ANOVA table (partial sum of squares)](image)

From this table, we can see that the factors does not interact or effect the data through interaction. Factor C, nozzle height, does not have effect on top kerf width for this material. Factor A and B does have significant effect and they also have quadratic effect on top kerf width. Figure 3 shows graphically on how the laser power and cutting speed effects the top kerf width for WPC.
From this we can now obtain the general equation which can be used to estimate the value of top kerf width by considering only the factors which are significant. Therefore, the final equation in terms of coded factors is given by:

$$R1 = 0.73 + 0.13A - 0.23B - 0.13A^2 + 0.55B^2$$

where $R1$ is response (top kerf width), $A$ and $B$ are factors $A$ and $B$ which are laser power and cutting speed respectively.

### 3.2. Optimization

With all the analysis done, we can now generate the numerical optimization of factors which will theoretically ensure an optimum cut quality for the material WPC using this CO$_2$ laser cutting machine. There has been 10 solutions being generated which shows the values of factors. Table 4 shows all the possible solutions generated.

Table 3: Solutions with a total 10 numbers of starting points

| No. | Laser power (%) | Cutting speed (mm/s) | Nozzle height (mm) |
|-----|-----------------|----------------------|--------------------|
| 1   | 77.08           | 3.84                 | 4.36               |
| 2   | 65.50           | 2.29                 | 4.50               |
| 3   | 74.28           | 3.44                 | 5.60               |
| 4   | 77.67           | 2.59                 | 5.39               |
| 5   | 65.51           | 3.18                 | 5.44               |
| 6   | 79.17           | 2.65                 | 5.17               |
| 7   | 68.15           | 3.18                 | 4.39               |
4. Conclusion
From this study, we can conclude that it is possible to machine WPC using CO$_2$ laser cutting machine when careful attention is given to the parameters involved in machining. Through this parameter optimization process, we are able to identify the best parameter that has to be set in order to get the best cut quality, which enables us to further increase the usage of WPC in the industry of internal house decorations. More specifically, we can now produce the traditional Malay wood carving, popularly known as 'papan pemanis’ which was previously made using wood through intricate process which needs high level human skills.

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