

OPTIMIZATION OF LASER CUTTING OF REINFORCED PVC SHEET

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Abstract: Composite sheets are widely used. These sheets are usually composites, consisting of a polymer matrix and fiber materials. Since there is a need for sheets in different sizes, they must be cut in parts. Several cutting technologies are used for this purpose, e.g., application of special knives, scissors, or water-jet. Besides their well-known benefits, there are some disadvantages, partly due to the direct connection between the tool and the material. To reduce, the application of laser beam cutting technology has expanded in the last decades. The purpose of our research was to test the application of a laser beam in cutting reinforced PVC sheet to find the optimal technology parameters. We found that a CO₂ laser machine can cut PVC-PA composite sheets with acceptable edge quality. Optimal parameter setting is $V = 100$ mm/s cutting velocity and $P = 30$ W laser power. The experiments could not prove the correlation among line energy, edge quality, and area of HAZ. V has a significant effect on tensile strength with 20 and 30 mm/s. The maximum tensile strength is 868 N for warp cutting direction, which was produced by $V = 25$ mm/s.

Keywords: PVC, reinforced polymer, laser cutting

INTRODUCTION AND LITERATURE

The laser beam application in cutting polymers is a popular technology because it offers excellent potential to process a wide variety of materials. [1] The surface quality aspects of laser cutting were investigated in the case of some polymeric and composite materials as polycarbonate (PC), polymethylmethacrylate (PMMA) (acrylic), polypropylene (PP), and thermoset plastics. Several levels of power, cutting velocity, and pressure settings were used during the process. At the preliminary tests, the following process parameters were used: the laser power and the cutting velocity were varied from 280 to 900 W, and 250–4000 mm/min, the thickness of the selected plates varied from 2 to 8 mm, and the range of gas pressure was 0.5–4 bar. The processing parameters used for the CO₂ laser cutting of PMMA and PC were as follows: laser power and the cutting velocity were varied from 250 to 650 W and 250–3500 mm/min. The thickness of the selected plates for the PMMA and PC was 6 and 3 mm. The pressure of the gas for CO₂ laser cutting PMMA and PC were 0.5 and 4 bar. The results showed that the heat-affected zone (HAZ) increases with laser power and decreases with the cutting velocity. The laser cutting workability of the polymers/composites: PMMA very high, PC high, PP high and medium, and thermosets plastics lower. [2]

CO₂ laser cutting application was also investigated to polyethylene (PE), polypropylene (PP), polycarbonate (PC) in different thicknesses ranging from 2 to 10 mm. Besides the parameters mentioned above, the values of kerf widths on top (L_{sup}) and bottom (L_{inf}) thicknesses, the melted transverse area, the melted volume per unit time, and surface roughness values (R_a) on cut edges were also measured during the process. According to the results, not always higher

cutting speeds are indicative of greater process efficiency. The laser cutting workability of the three polymers is as follows: PC high, PP medium-high, and PE lower. [3]

The laser process was also used for the cutting of medium-density fibreboard (MDF). The CO₂ laser was used during the operation in continuous wave and pulse mode also to compare the cut quality results. In constant wave, results showed that the average kerf width obtained for MDF reduced with increasing cutting speed for most material thickness. The experimental results also showed that the greater the cutting speed, the less time there was for heat to diffuse sideways through the cut surfaces and the narrower the HAZ. In the case of pulse mode, the difference in Ra and the kerf width was slight. [4]

In another application of a 60W CO₂ laser on polycarbonate sheet with a thickness of 3.2 mm they concluded that by decreasing the laser focal plane position and laser power, the bottom kerf width was reduced, and the bottom kerf decreases if the cutting speed increases. The cutting quality is better if the laser spot point locating in the depth of the workpiece. The optimum process parameters were as follows: cutting speed 16 mm/s, laser power 40W, focal plane position 1.8 mm. [5]

Carbon fiber reinforced plastics (CFRP) show a high potential for use. Laser cutting of the CFRP was examined in more aspects. The applicability of the laser remote cutting process and the gas-assisted laser cutting of CFRP were analyzed. Based on the experiments' results, both are suitable to cut the CFRP material [6]. In another investigation, a systematic analysis of the hazardous substances emitted during laser cutting of CFRP with thermoplastic and the thermosetting matrix was demonstrated. The result of the mass-spectrometric analysis was that the emissions of dangerous substances are significant. However, it is possible to minimize these hazardous substances in the workplace, not to exceed the thresholds. [7] The quality of the cut surface and the material properties were influenced using laser cutting. The cutting process is improved, and fewer errors occur if adding light-absorbing soot particles to the matrix's resin. [8]

The experiments introduced above did not apply CO₂ laser to process PVC sheet, so its optimal values of technology parameters are not identified yet. We prepared experiments to identify applicable technology window and optimal values of power and velocity to fill this gap.

SPECIFICATION OF MATERIALS AND EQUIPMENT

Test material is produced by Tuplex. Its most important features are the followings:

- Excellently compatible with UV curable digital printers;
- Perfect printing impression with stable ink absorption and low ink consumption;
- Good physical strength in longitude and latitude;
- High glossy and smooth surface;
- Matte back prevents stickiness.

The technical properties are presented in Table 1.

Table 1: Technical properties of test material

Product name	Tuprint Frontlit Banner, C1010-450
Chemical Compound	Polyvinyl-chloride (PVC) and Polyester (PE)
Base Fabric	1000D*1000D polyester yarn
Area Density	510 g/m ²
Fabric Thickness	0,376 mm
Warp density	63 pcs/100 mm
Weft density	72 pcs/100 mm

The material was cut by an ALFA LCE – 2 CO₂ Laser machine. Images were created by JINGOU Portable USB Digital Microscope and were assessed by ImageJ software.

EXPERIMENTS

Preparatory Experiments

The purpose of the preparatory experiments was to identify the technology window provides acceptable edge quality. Parameter settings of preparatory experiments are shown in Table 2.

Table 2: Parameter settings of preparatory experiments

Power of laser beam (varied)	10 – 60 W (with 10 W step)
Cutting velocity (varied)	10 – 100 mm/s (with 10 mm/s step)
Focus distance (constant)	58 mm
Cutting length (constant)	850 mm
Mode (constant)	Pulse, 20 kHz
Direction of irradiation (constant)	Back non-printed side of sheet
Direction of cutting (constant)	Weft

One 30 cm long cut was made for every combination of varied parameters (demonstrated in Figure 1). From each cut 3, 10 mm length section was selected for the assessment of edge quality.



Figure 1: Some of the cuts on the back side of PVC sheet

The area of Heat Affected Zone (HAZ) was measured by ImageJ software.

The values of the area of HAZ for different laser parameters are shown in Table 3 and Fig. 2.

Table 3: Area of HAZ measured by ImageJ software with settings I

Area of HAZ [mm ²]		Laser power [W]				
		20	30	40	50	60
Cutting velocity [mm/s]	10	5,493E-01	6,117E-01	4,833E-01	6,080E-01	5,927E-01
	20	3,223E-01	3,603E-01	3,920E-01	3,470E-01	2,673E-01
	30	4,217E-01	3,893E-01	3,787E-01	3,637E-01	2,937E-01
	40	8,543E-01	3,863E-01	3,783E-01	3,883E-01	3,317E-01
	50	8,617E-01	3,900E-01	3,693E-01	3,780E-01	3,483E-01
	60	6,433E-01	2,087E-01	2,547E-01	3,217E-01	2,183E-01
	70	7,550E-01	3,300E-01	3,923E-01	2,507E-01	2,760E-01
	80	1,115E+00	5,510E-01	4,647E-01	4,567E-01	3,737E-01
	90	1,012E+00	4,313E-01	4,873E-01	4,827E-01	4,233E-01
	100	8,600E-01	1,823E-01	1,940E-01	2,550E-01	2,747E-01

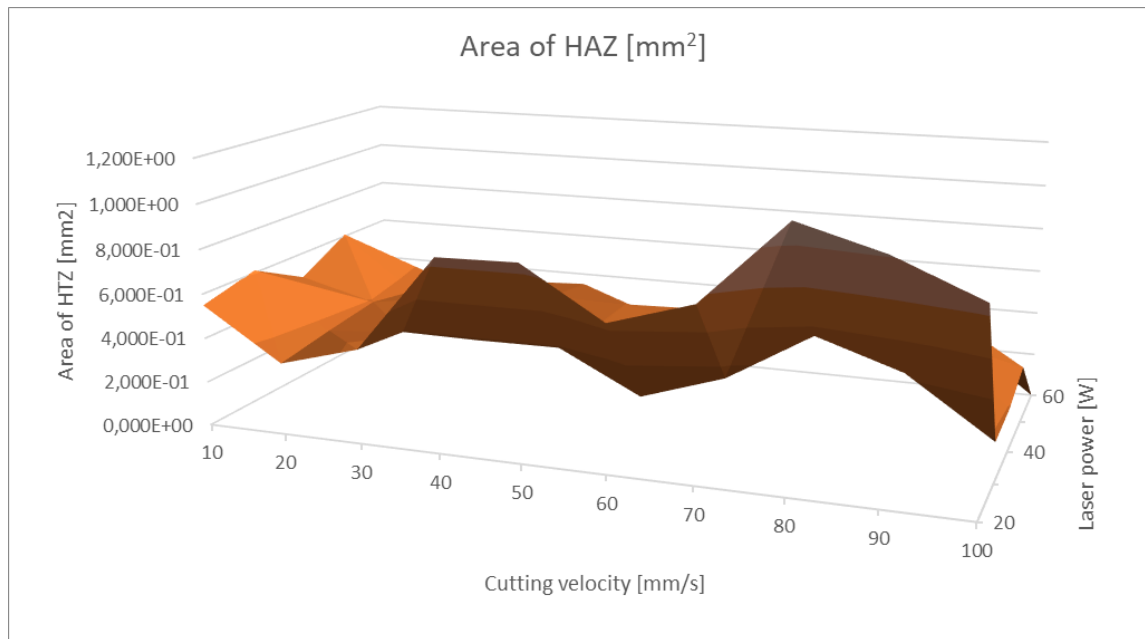


Figure 2: Area of HAZ measured by ImageJ software with settings I

Edge qualities of the selected 3 sections were analyzed by visual inspection by two inspectors too. If HAZ could be seen by eyes without a microscope, the result of qualification was 1. Since two inspectors checked 3 sections, the maximum level of negative qualification for each specimen is 6.

Based on the inspection, the following conclusions could be drawn:

- With 10 W laser power, the sheet could not be cut, which means that more than 10 W is needed to cut the material tested.
- At 10, 20, and 30 mm/s velocity the area of HAZ could not be recognized by eyes.
- At 20 W laser power, HAZ could be measured by microscope in case of every velocity, but could not be detected by eyes below 30 mm/s. The area of HAZ was bigger than that of all of the other values of power above 30 mm/s. The detected area was the yellow zone of the sheet, probably caused by condensed gases of ingredients.
- Another HAZ peak was detected by ImageJ measurement at 10 mm/s velocity. The area of HAZ was increased by the increase of power. However, this HAZ could not be recognized by visual inspectors. This might be caused by the continuously changing grey colour of this zone, which made it difficult to detect by eyes, but it could easily be measured by microscope.
- From the processing point of view, we need high velocity for small cycle time and low power for cost-effectiveness, resulting in acceptable edge quality, so if we assume that the PVC sheet was homogeneous, the optimal combination of parameters is $V = 100$ mm/s and $P = 30$ W.

To identify the correlation between laser settings and assessment results, we compared the values of line energy, visual qualification, and area of HAZ [see in Figure 3, Figure 4, and Figure 5. Line Energy is defined as the ratio of laser power [P] to cutting velocity [V] [8].

$$E = \frac{P}{V} \left[\frac{J}{mm} \right] \quad (1)$$

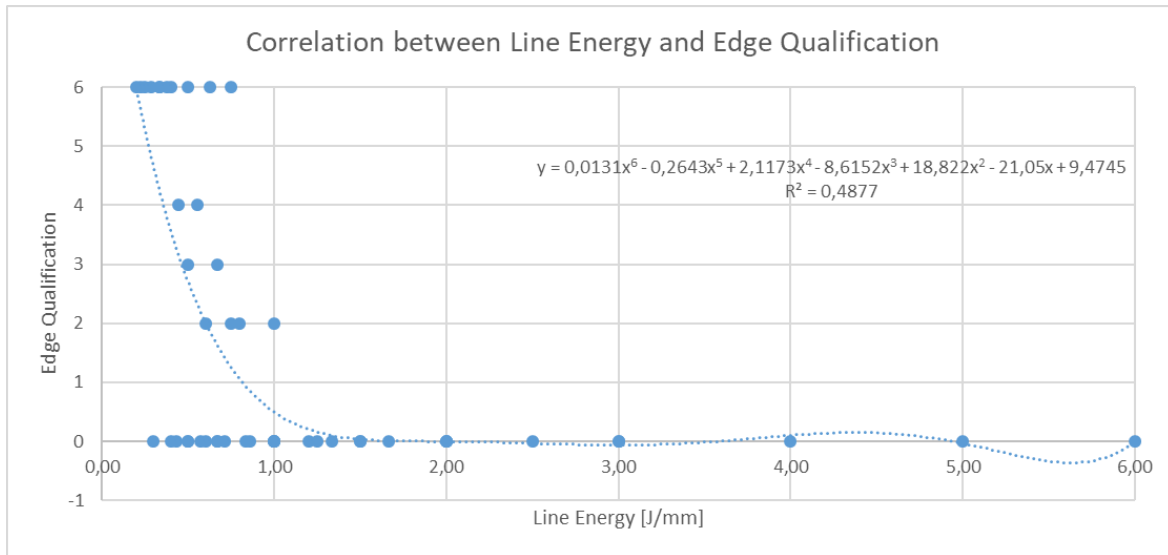


Figure 3: Correlation between Line Energy and Edge Qualification

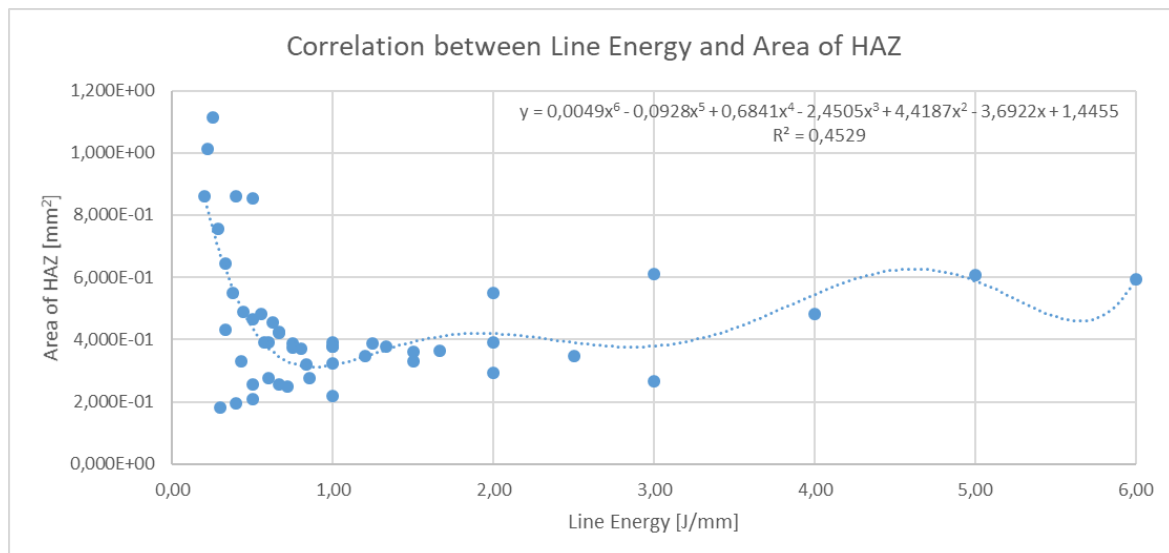


Figure 4: Correlation between Line Energy and Area of HAZ

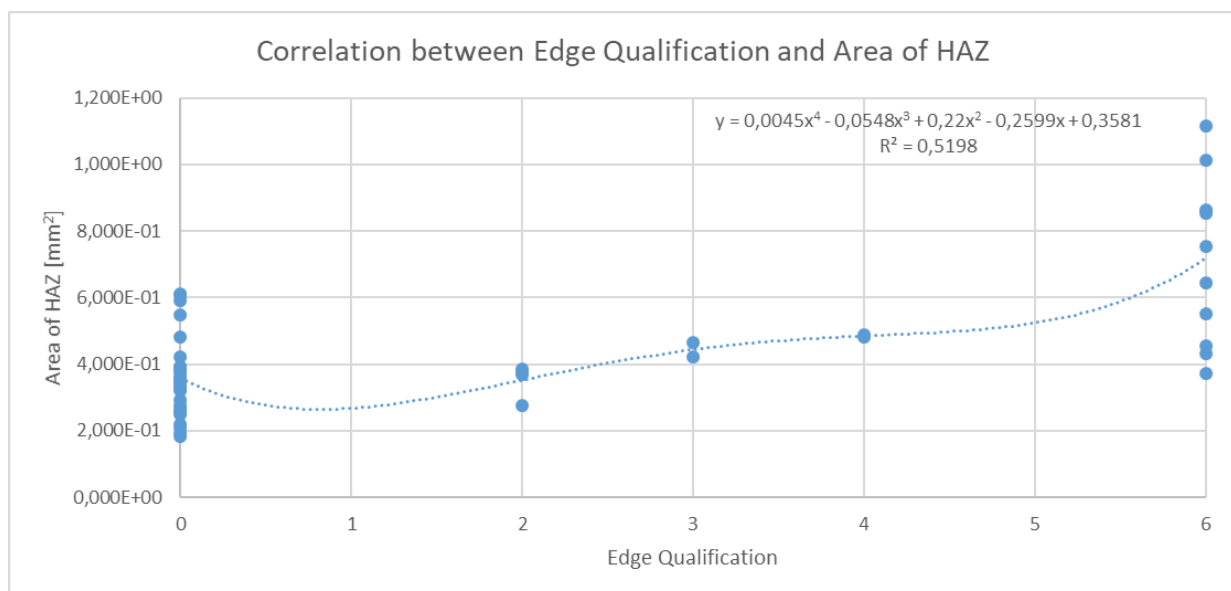


Figure 5: Correlation between Edge Qualification and Area of HAZ

Results show that there are not correlations among these factors, which means there must be other factors that influence edge qualification. Besides, there is no correlation between the Area of HAZ and visual qualification.

Assessment of HAZ for Negatively Qualified Specimens

We measured HAZ with different ImageJ settings too [see in Figure 6] to check whether the correlation between factors could be identified if we take only unaccepted specimens into consideration. The value of brightness was set to harmonize with the visual detectability, which means that those specimens that were accepted by visual instructors have zero HAZ.

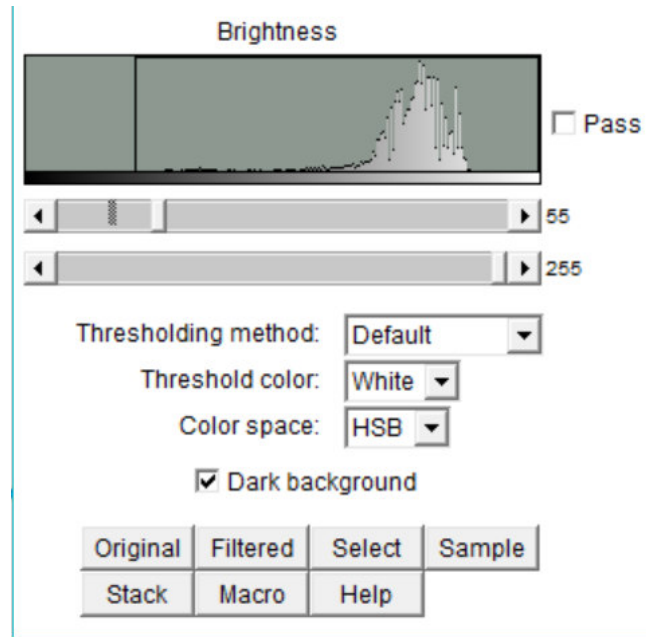


Figure 6: Settings II of threshold color in ImageJ for the measurement of the area of HAZ

The areas of HAZ measured by new settings for previously unaccepted specimens by visual inspection are presented in Table 4 and Figure 7.

Table 4: Area of HAZ measured by ImageJ software with settings II

Area of HAZ [mm ²]		Laser power [W]				
		20	30	40	50	60
Cutting velocity [mm/s]	40	1,933E-02	1,500E-02	N/A	N/A	N/A
	50	1,367E-02	N/A	1,788E-03	6,000E-03	N/A
	60	4,247E-03	N/A	N/A	N/A	N/A
	70	2,816E-03	N/A	N/A	N/A	N/A
	80	5,526E-03	6,000E-03	5,493E-03	6,370E-03	2,221E-03
	90	7,411E-03	1,667E-03	4,347E-04	1,000E-02	5,339E-04
	100	7,124E-04	N/A	N/A	N/A	1,955E-04

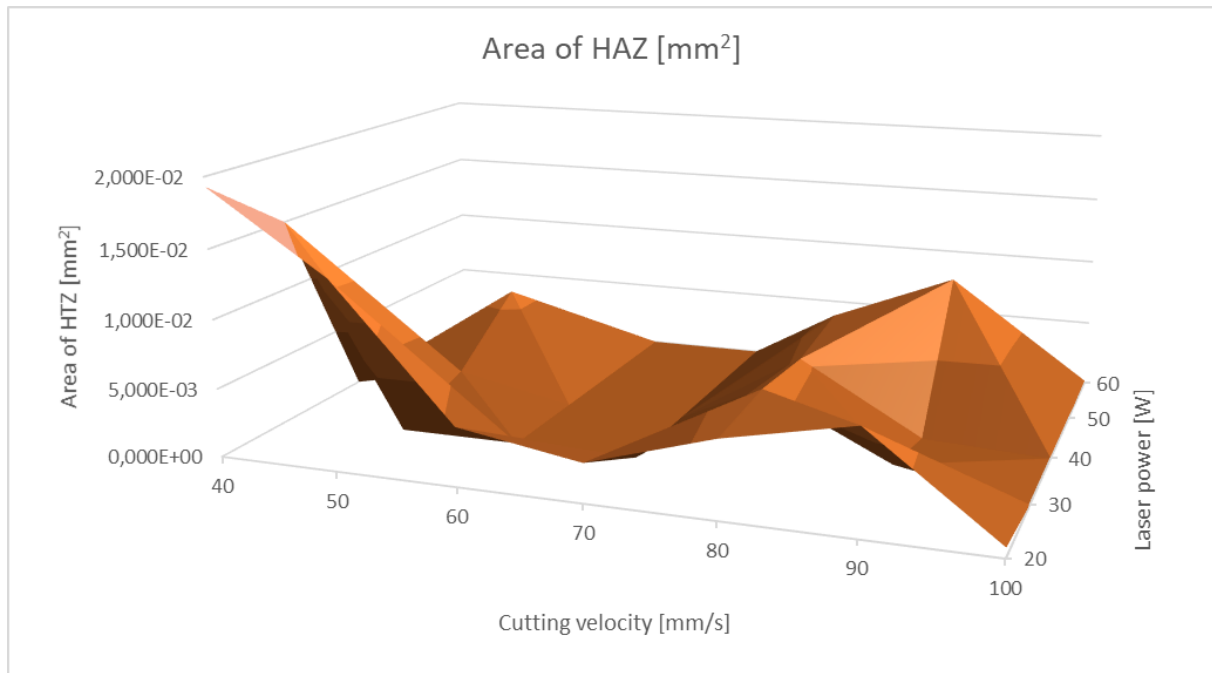


Figure 7: Area of HAZ of visually unaccepted specimens, measured by ImageJ setting II

We can conclude that a strong correlation could not be found between any of the factors.

Assessment of Mechanical Properties

The purpose of the next experiment was to assess the connection between cutting technology parameters and tensile strength expressed in maximum force $[F_{\max}]$. We applied both thermal and mechanical effects. The list of independent or input variables is specified in Table 5. The list of dependent or output parameters is specified in Table 6.

Table 5: Input parameters of cutting experiment

Power of laser beam (varied)	40, 45, 50, 55, 60 W
Cutting velocity (varied)	20, 25 and 30 mm/s.
Cutting method (varied)	A laser beam, knife, scissors
The direction of cutting (varied)	Weft and warp

Table 6: Output parameters of cutting experiment

Maximum tensile force [N]
Elongation [%]

The design of the experiment is specified in Table 7. The number of specimens is 5 for every combination.

Table 7: Design of cutting experiment

ID.	Laser power [W]	Cutting velocity [mm/s]	Cutting method	Direction of cutting
1	40	20	laser	weft
2	40	20	laser	warp
3	40	25	laser	weft
4	40	25	laser	warp
5	40	30	laser	weft
6	40	30	laser	warp
7	45	20	laser	weft
8	45	20	laser	warp
9	45	25	laser	weft
10	45	25	laser	warp
11	45	30	laser	weft
12	45	30	laser	warp
13	50	20	laser	Weft
14	50	20	laser	Warp
15	50	25	laser	Weft
16	50	25	laser	Warp
17	50	30	laser	Weft
18	50	30	laser	Warp
19	55	20	laser	Weft
20	55	20	laser	Warp
21	55	25	laser	Weft
22	55	25	laser	Warp
23	55	30	laser	Weft
24	55	30	laser	Warp
25	60	20	laser	Weft
26	60	20	laser	Warp
27	60	25	laser	Weft
28	60	25	laser	Warp
29	60	30	laser	Weft
30	60	30	laser	Warp
31	Manual	Manual	scissors	Warp
32	Manual	Manual	knife	Warp
33	Manual	Manual	scissors	Weft
34	Manual	Manual	knife	Weft

Comparing thermal and mechanical processing, results do not prove that there is a significant difference between their effects on tensile strength. Results show that only cutting velocity has a significant effect on tensile strength at 0,05 significance level (Figure 8).

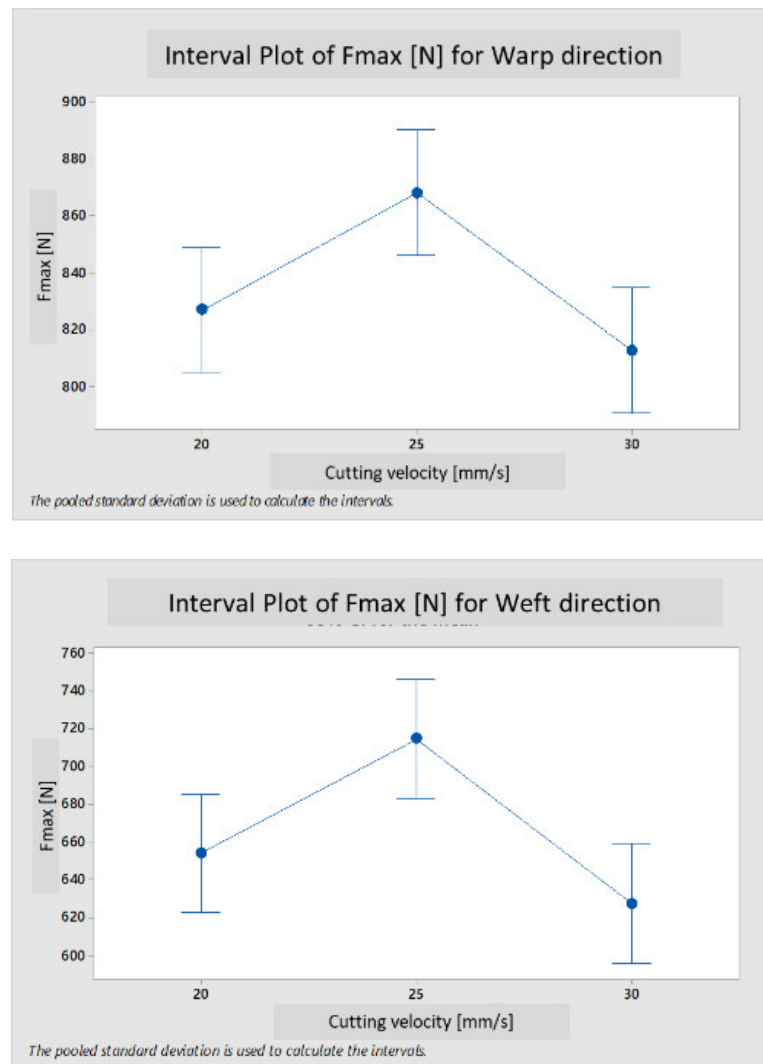


Figure 8: Results of One-way ANOVA: a) cutting in the warp direction (P -Value is 0,002); b) cutting in weft direction (P -Value is 0,001)

The optimal value of cutting velocity is 25 mm/s for both cutting directions. The maximum value of average tensile strengths is 868 N for warp direction and 714 N for weft direction (Figure 9 and Figure 10). For weft direction, cuttings by all the velocities result in higher tensile strength than that of mechanical cutting (Figure 9). For warp direction, the cuttings with knife and scissors result in higher tensile strength than that of laser beam cutting at 20 and 30 mm/s, while there seems not to be a significant difference between the result of mechanical cuttings and thermal cutting at 25 mm/s velocity (Figure 10). Weaker strength can be caused by the bigger HAZ, but this could not be detected. Another reason can be the heterogeneity of material.

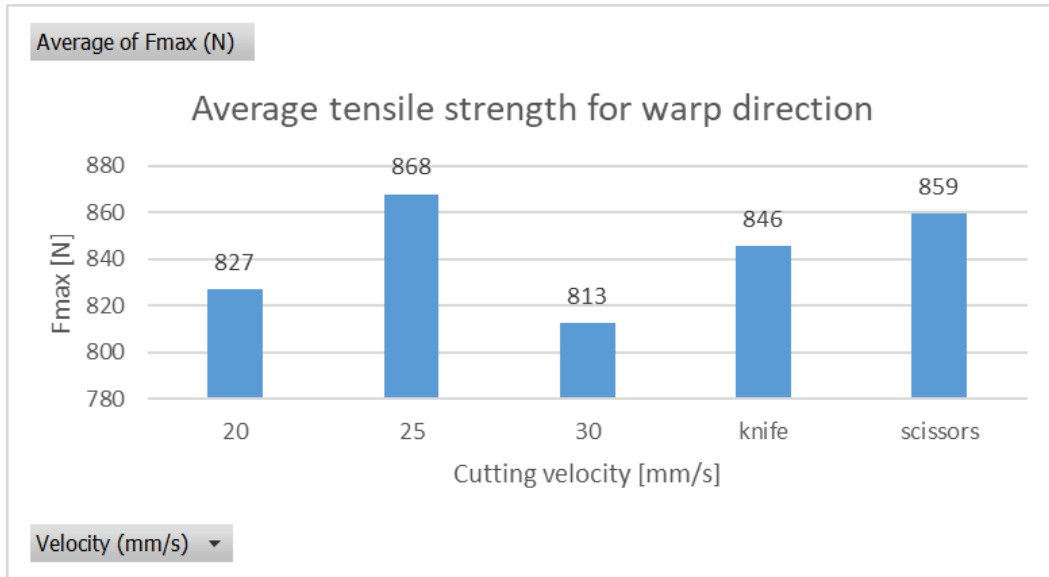


Figure 9: Effect of the velocity of cutting [mm/s] in warp direction on tensile strength (F_{max} [N])

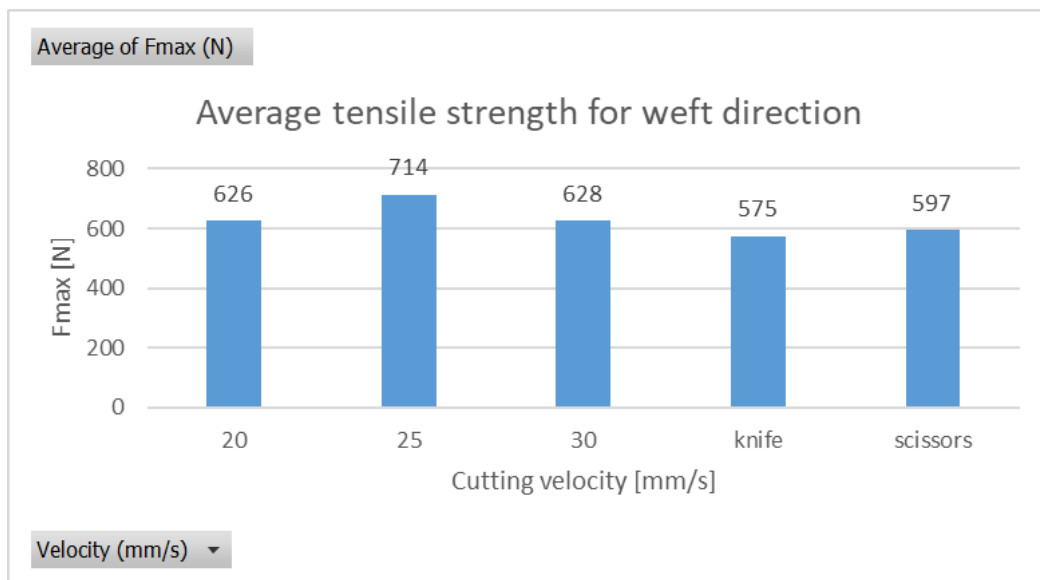


Figure 10: Effect of the velocity of cutting [mm/s] in weft direction on tensile strength (F_{max} [N])

CONCLUSIONS

PVC-PA composite sheets can be cut by a CO₂ laser machine with acceptable edge quality. Optimal parameter setting is $V = 100$ mm/s cutting velocity and $P = 30$ W laser power. The correlation among line energy, edge quality, and area of HAZ could not be proved by the experiments. V has a significant effect on tensile strength with 20 and 30 mm/s. The maximum tensile strength is 868 N for warp cutting direction, which was produced by $V = 25$ mm/s. The effect of laser power on tensile strength could not be proved between 40 and 60 W.

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