Qualification of Blue Laser Cutting Tool and Design of Test Procedure for Determining Cutting Parameters

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Abstract

Laser cutting with the XYZprinting Da Vinci 1.0 Pro 3D printer with a laser engraving module requires process parameter determination in order to perform accurately. The effect of changing the program's parameters to cut quality was investigated with the final goal of being able to consistently predict the appropriate parameters for a complete cut. This Indium-Gallium-Nitride laser (λ = 450nm) with power output of 385mW has the ability to engrave paper, wood, leather, cardboard, and plastic. For simplicity in the qualification of this laser, cutting, not engraving, of paper substrates was investigated. The XYZprinting Da Vinci 1.0 in vector mode allows the control of cutting parameters "engraving speed" and "engraving layers". Assuming that the laser light energy is only absorbed or reflected (not transmitted) and the laser intensity exhibits a spatial profile following the TEM_{00}, a model was derived to determine predicted values of cutting velocity and layers needed to cut through paper of given thickness and color. Using this model and known values of paper absorbance, the cutting velocity for a variety of paper types was calculated and tested. The mathematical model was found to be accurate for most paper colors. High absorption paper colors resulted in the highest level of agreement – the predicted cut velocity produced suitable cuts. Using white or blue colored paper, however, does not result in optimal cuts with the predicted cut velocity. Their measured velocity to produce suitable cuts diverges the most from the model so more investigation is required to model these cases.

Keywords: Laser cutting, Indium-Gallium-Nitride, paper substrate, TEM_{00}, absorption

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3. Problem Statement

In order to use the laser cutter effectively, it is critical to cut quality to define and validate the cutting parameters. In this project, a procedure was developed and the effect of changing cutting parameters (velocity and layers or passes) was investigated through mathematical modeling and experimental validation. The objective of this project was to consistently predict the appropriate cutting parameters for varying paper types in order to produce optimal cuts.

4. Introduction

4.1 Lasers

A LASER (Light Amplification by Stimulated Emission of Radiation) is a device that provides a stream of coherent light waves. The coherency of the light waves is what allows the heat intensity on the workpiece surface to be large enough to cause material removal. Light amplification is achieved through stimulated emission of the photons. In semiconductor lasers, stimulated emission of the laser medium behaves similar to an LED when an external potential is applied. The increased energy allows holes from the p-type region and electrons from the n-type region to recombine, emitting a photon in the process (Figure 1b).[1]

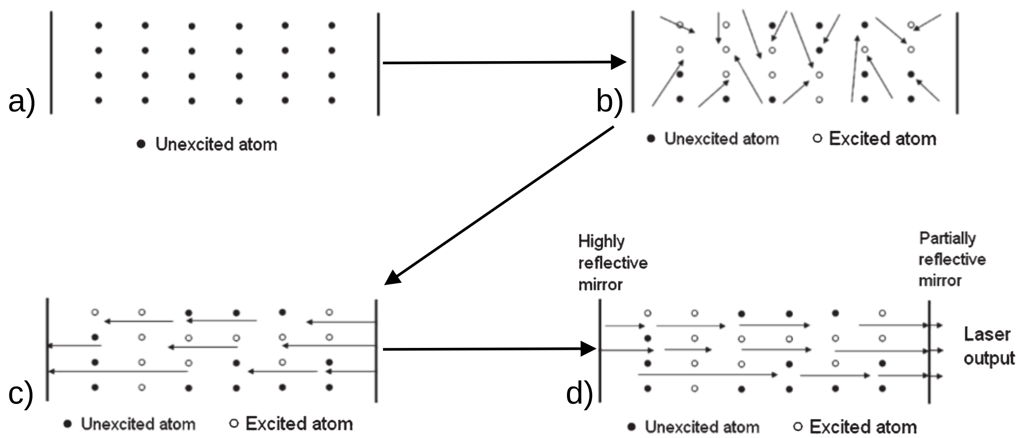

Figure 1 – Schematic of light amplification stages: (a) initial unexcited state (laser off), (b) optical pumping resulting in an excited state, (c) stimulated emission, and (d) amplification of light.

Stimulated emission is a process during which the previously emitted photons are absorbed by an electron in an excited state. This stimulated electron then emits two photons in the same direction and of exactly the same wavelength, thus amplifying the original photon (Figure 1c). The amplification of the light then continues with the aid of mirrors. One highly reflective mirror (100% reflective) allows all the photons that were emitted by the stimulation of electrons to be entirely reflected back into the laser medium, continuing the stimulate emission process. The second mirror is only partially reflective, which allows a portion of the laser energy to escape (Figure 1d). For laser cutters, the beam is then channeled through a wave guide and focused with a lens onto the workpiece. The lens allows the light output to change beam width and focal plane, with minimal diffraction, giving it exceptional intensity and directional flexibility.

4.2 Laser Cutting

Lasers are used in many applications, including military, medical, commercial, and industrial. Industrial applications of high powered lasers include various machining processes, such as cutting, welding, and drilling. Laser cutting is a material removal process in which a laser is focused onto the surface, causing the melting or burning away of material. With relative movement of the laser beam, cuts can be generated. When the laser beam comes in contact with the material, light is reflected, absorbed, transmitted, and scattered. The scattered and transmitted light is not taken into account in this project. The reflected light energy is lost to the environment and is the largest factor that contributes to a low energy efficiency. The absorbed light energy is the factor that allows laser cutting to occur. The absorbed energy manifests as lattice vibrations in the material which transfer the light energy to thermal energy. If the thermal energy is sufficient enough to raise the material to its melting or auto-ignition temperature, material can be removed. Paper's auto-ignition temperature is 450°C, at which point paper will spontaneously combust and thus, be vaporized.[2]

4.3 Sustainability

The motivation behind this project lies with an attempt to study a material processing method that has the potential to aid the endeavor to become a more sustainable society. Sustainability is a global concern in light of the ongoing degradation of the environment, with population growth being the largest contributor. There are many goals in establishing a sustainable environment, but only one related to the use of materials – resource consumption. In order to keep up with the modern technological advances, natural resource use, energy use, and waste production have all increased significantly in the past decades. Natural resources are slowly running out as industries continue to produce, constant use of energy causes CO_2 emissions, and the increased manufacturing and use of materials is producing large amounts of waste. The two main factors of sustainability that are associated with laser cutting are energy use and waste production.

4.3.1 Energy Efficiency

While laser cutting is desirable for its many advantages, it is still energy intensive and energy inefficient compared to conventional machining. Industrial settings currently use the CO_2 laser.[3] Current CO_2 lasers only have a 10% power efficiency while the newer fiber lasers have as much as 30% power efficiency.[3, 4] If a process is less energy efficient, it takes more energy to perform a task compared to counterparts. Between the CO_2 and fiber lasers, it takes significantly more energy to operate the former. Improving energy efficiency will reduce the total energy needed for material processing.

4.3.2 Waste Production

The second main aspect of a sustainable process is the waste produced. Solid waste consists of debris, residue, and worn out tools from the machining process. Solid debris, from mechanical machining, needs to be collected and disposed of causing potential environmental problems. Because of the isotropic properties of metals, metal scrap can be re-processed in material production, however, materials like polymers or composites are hazardous to both humans and the environment. Polymers degrade slowly and release toxic chemicals and composites contain microfibers, which can cause health problems. Liquid waste is common to mechanical machining methods as well. Oil-based cutting fluids are commonly used to lubricate and control the temperature of the material at the cut site as to minimize alteration mechanical properties.[4] The disposal of such cutting fluids can cause environmental pollution. Laser machining does not produce solid or liquid waste, but it will produce gaseous waste. The fumes that are produced are a possible health hazard to workers. Fumes can contain particles that will cause respiratory tract irritation if inhaled. Most of the solid or liquid material and debris that is produced during laser cutting will be vaporized from the high energy laser. Gaseous waste can be captured and released once it is filtered for any hazardous particles or compounds.

5. Experimental Procedures

5.1 Mathematical Model

5.1.1 Derivation

The various physical phenomena that occur when the laser beam hits the material surface are energy scattering, absorbance (α), reflectance (γ), and transmittance (τ). The effects of light scattering are included in the reflectance parameter. The resulting relationship is given by:

$$\alpha + \gamma + \tau = 1 \qquad (1)$$

Since the main substrate under investigation is not transparent, it was assumed that transmission also does not have a significant effect ($\tau = 0$). The absorption of energy is what causes the material to heat and vaporize once the paper reaches its auto-ignition temperature, so the factor of α is the most critical in the mathematical model. A theoretical model that estimates the velocity required for a successful cut is based on a Gaussian energy intensity distribution of the laser beam. The transverse mode of a laser is a particular electromagnetic pattern measured perpendicular to the propagation direction of the beam. The common assumption for laser machining applications is that the mode of the laser is in Transverse Electromagnetic Mode, TEM_{00} (Figure 2).[1]

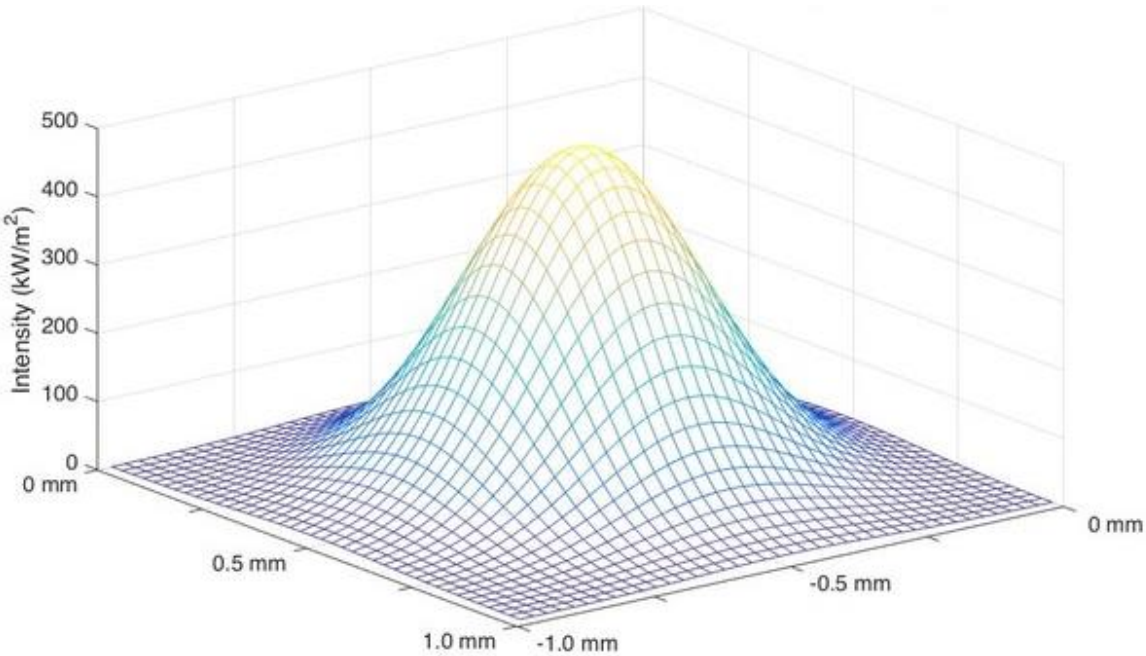

Figure 2 – Laser in Transverse Electromagnetic Mode (TEM_{00}) showing a Gaussian spatial distribution.

By assuming the beam has a circular cross-section, it will move with a defined velocity along a central line in the x-direction, as shown in Figure 3.

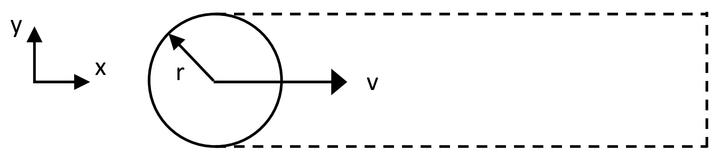

Figure 3 – Top view of circular cross-section of laser beam predicted cut area resulting from motion of laser along x-direction.

Given the Gaussian distribution of laser intensity and a circular beam moving in one direction, the intensity is given by:[5]

$$I\left(\frac{W}{m^2}\right) = I_0 e^{-\left(\frac{x}{r}\right)^2} \tag{2}$$

Where I_0 is the peak intensity of the laser, r is the beam radius, and x is the distance from the center of the beam. For a beam with power output, P, and a substrate with absorbance, α, the peak intensity is given by:

$$I_0 = \frac{\alpha P}{\pi r^2} \tag{3}$$

A moving beam will produce a rectangular cut with area A, as shown in Figure 3 by the dotted lines. The resulting area and intensity produces a power output of the laser as follows:

$$P = IA = AI_0 e^{-\left(\frac{x}{r}\right)^2} \tag{4}$$

The energy absorbed by the defined area can be defined as the power multiplied by the exposure time, t. This relationship can be correlated to the velocity as follows:

$$E = Pt = AI_0 e^{-\left(\frac{x}{r}\right)^2} \left(\frac{\Delta x}{v}\right) \tag{5}$$

For a given paper substrate, the energy needed to raise the temperature to its auto-ignition temperature, is given by:

$$Q = mC_p\Delta T = \rho A \left(\frac{\Delta z}{N}\right) C_p \Delta T \tag{6}$$

Where C_p is specific heat, ΔT is the change in temperature from room temperature (25°C) to the auto-ignition temperature of paper (450°C), and m is the mass of material vaporized. This equation can be modified as to relate mass to density (ρ), area, and penetration depth of the laser, which can be related to the thickness of the paper, Δz, and N, the number of passes of the laser. By equating Eq. 5 and Eq. 6, they become an integration equation: [5]

$$\Delta z = \frac{I_0 e^{-\left(\frac{x}{r}\right)^2} N}{\rho C_p \Delta T v} \Delta x \tag{7}$$

$$z = \frac{N}{\rho C_p \Delta T v} \int_{-\infty}^{\infty} I_0 e^{-\left(\frac{x}{r}\right)^2} dx$$

$$= \frac{2 I_0 r N}{\rho C_p \Delta T v} \int_{0}^{\infty} e^{-\left(\frac{x}{r}\right)^2} d\left(\frac{x}{r}\right) \tag{8}$$

After integrating the Gaussian integral and substituting in Eq. 3, the velocity needed for a cut is:

$$\vec{v} = \left(\frac{P}{r\sqrt{\pi}}\right)\left(\frac{1}{\rho C_p \Delta T}\right)\left(\frac{N\alpha}{z}\right) \tag{9}$$

The parameters P and r are given by the equipment. The variables α, z, ρ, ΔT, and C_p are properties of the substrate. The cut velocity can be calculated corresponding to N, which is an equipment parameter that is arbitrarily set from 1-20. It is useful to note that there is a linear relationship between the number of passes and the cut velocity.

5.1.2 Material and Equipment Parameters

A summary of the constants used for cellulose-based paper can be seen in Table I. The laser engraving module defines a power output of 385mW, which is the value used in calculating predicted cut velocities. The density was manually calculated based on the weight and volume of standard 8.5”x11” printer paper. The absorbance values used for predictions were calculated from measured values of reflectance using Eq. 1 with the assumption that transmission does not occur. The known values of reflectance were taken from online source data produced by an OMRON photoelectric sensor (Figure 4).[6]

Table I. Equipment and Material Parameters

P (W)	0.385
r (mm) [7]	0.5
z (mm)	0.1
ρ (kg/m^3)	757.6
C_p (J/molK) [8]	1350
ΔT (K) [2]	425

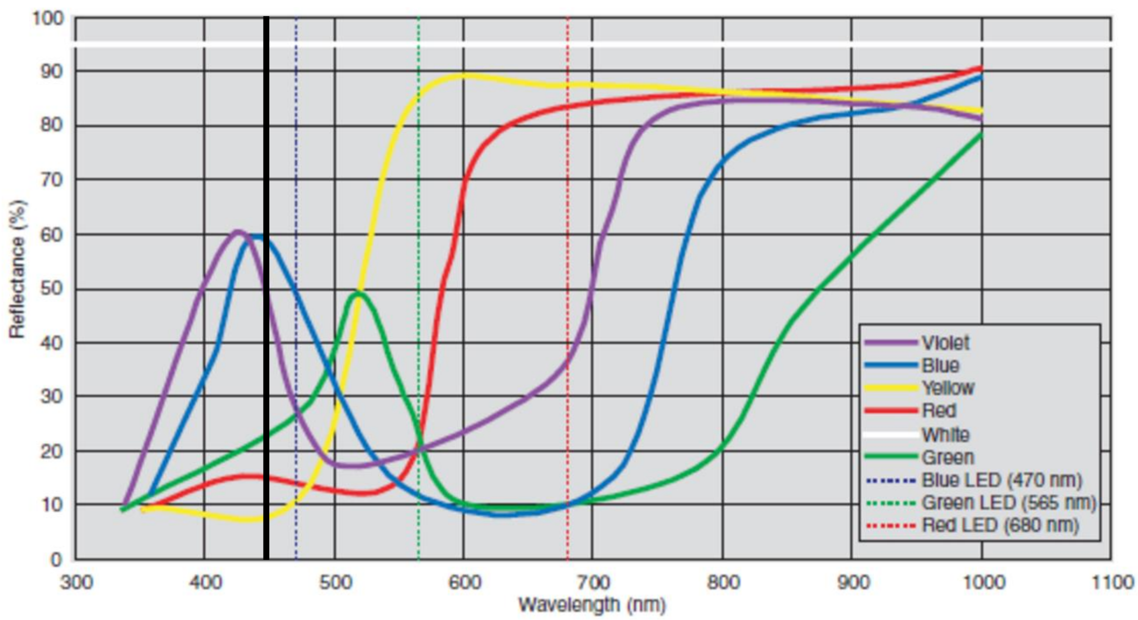

Figure 4 – Reflectance values from an OMRON photoelectric sensor with black vertical line highlighting reflectance values corresponding to λ = 450nm

5.1.3 Graphical Analysis

The variation in cut velocity with substrate thickness and absorbance, given N = 1, can be seen in the 3D surface (Figure 5). The velocity is directly proportional to absorbance and inversely proportional to substrate thickness.

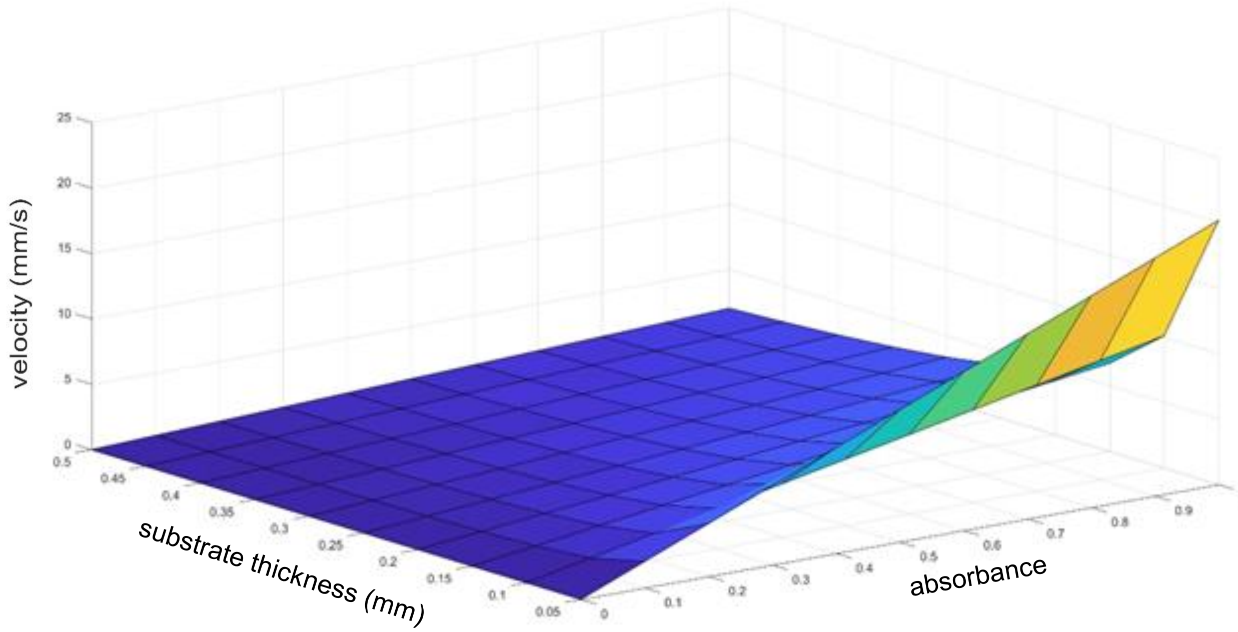

Figure 5 – Surface plot of thickness and absorbance effects on cut velocity given 1 laser pass.

The relationships between cut velocity and the independent variables, α and z, can be more clearly shown in 2D views of the above surface plot. Figure 6 shows that cut velocity and absorbance are directly related, confirming what was derived in Eq. 9. The varying slopes correspond to varying thicknesses such that the steepest slope corresponds to the smallest thickness. Figure 6 shows that with decreasing thickness values, the velocity becomes more dependent on absorbance. Figure 7 shows that the cut velocity and substrate thickness are, in fact, inversely related. In this graph the similarly shaped lines correspond to varying absorbance values. With this observation, Figure 7 shows that at small values of thickness, the absorbance has a larger effect on cut velocity.

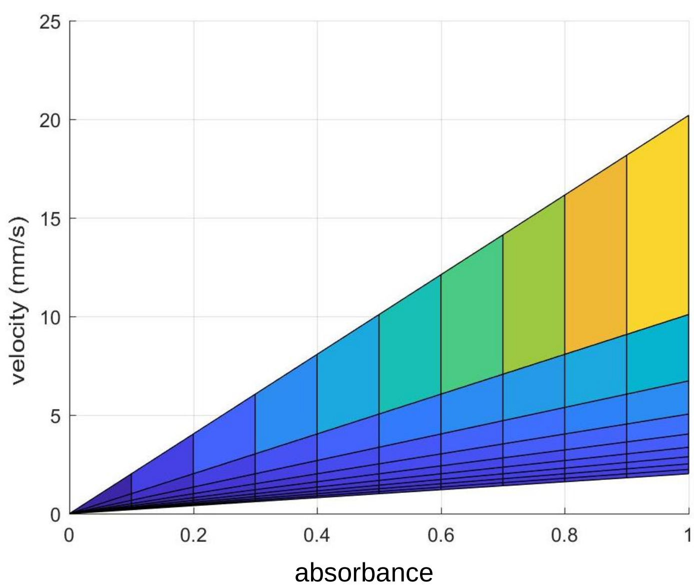

Figure 6 – Graph depicting the direct relationship between cut velocity and absorbance.

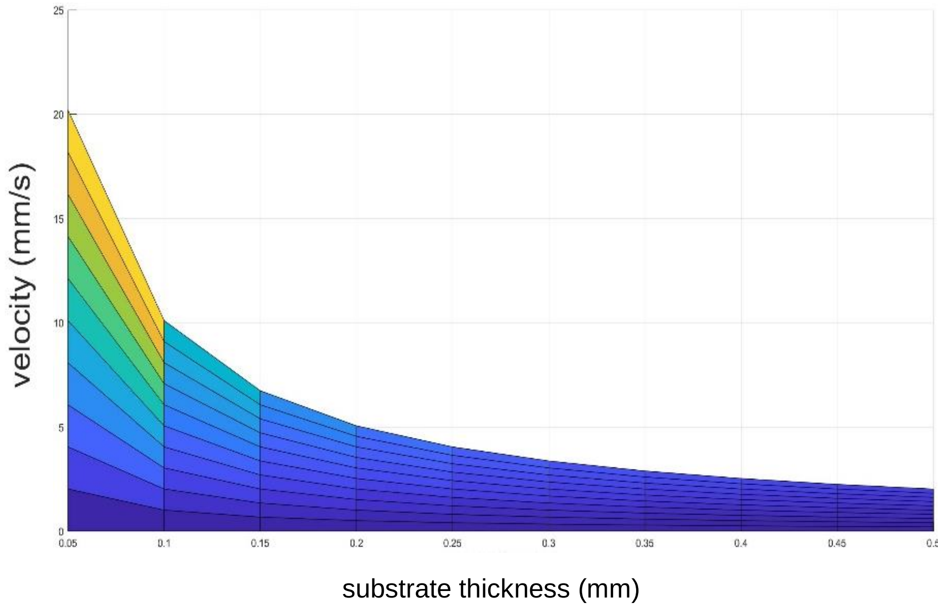

Figure 7 – Graph depicting the inverse relationship between cut velocity and substrate thickness.

5.2 Validation Testing

According to Eq. 9, predicted cut velocities can be calculated for various paper colors. In order to test the accuracy of this equation, these predictions were validated. In order to simplify the equation, the number of passes was set to 1 and only printer paper was used, such that z = 0.1mm. The predicted velocity and corresponding N value were inputted into the XYZprinting laser engraving program and a cut was produced. The predicted velocities were then adjusted to produce the optimal cut, which is defined as the desired design being complete, through the paper, and with minimal charring (Figure 8). The adjusted value is what is recorded as the "Measured v". For example, if the cut was incomplete, the value of velocity was decreased until a successful cut was made. If there was a visible amount of charring, the velocity was increased. Once the optimal velocity was experimentally determined, a percent difference from the modeled velocity was calculated to highlight the accuracy of the derived model.

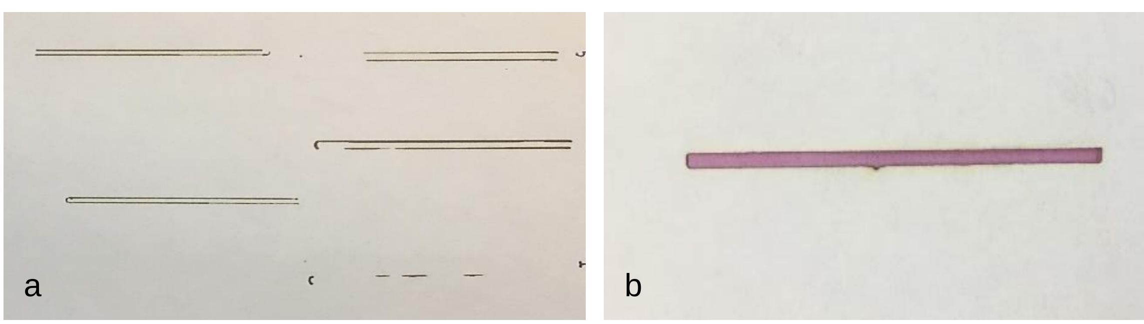

Figure 8 – Images showing (a) incomplete, not optimal cuts and (b) optimal cut.

6. Results and Discussion

The data from the validation testing for a representative sample of tests is summarized in Table II. Again, these values assume the thickness is set at 0.1mm and the layers are set to 1.

Table II. Predicted and Measured Cut Velocity Comparison for Printer Paper

Absorption (with corresponding paper color)	Predicted v (mm/s)	Measured v (mm/s)	Percent Difference (%)
0.05	0.50	2.5	133.4
0.4	4.00	6.1	41.6
0.75	7.50	8.1	7.75
0.85	8.50	8.6	1.22
0.9	8.99	8.1	10.5

As stated earlier, the values of absorbance were calculated from measured values of reflectance which were taken from online source data produced by an OMRON photoelectric sensor.[6]

Evaluating the percent difference calculated, absorbance values corresponding to white and blue colored paper produce cut velocities that deviate the most from predictions. A deviation can be higher or lower than the predicted cut velocity. The measured cut velocity for white paper is 5 times that of the prediction and for blue paper it is 1.5 times larger. All other colors have measured cut velocities closer to those predicted. It should be noted that although the cut velocity for white and blue paper deviates from predictions, the deviation is larger than the prediction. This indicates that the prediction will produce a cut, but resulting cut is not optimal – it has significant charring present. A larger “Measured v” indicates that a more aesthetically pleasing cut will result. The comparison between predicted and measured cut velocity can also be seen visually, by looking a predictive range of cut velocity (Figure 9).

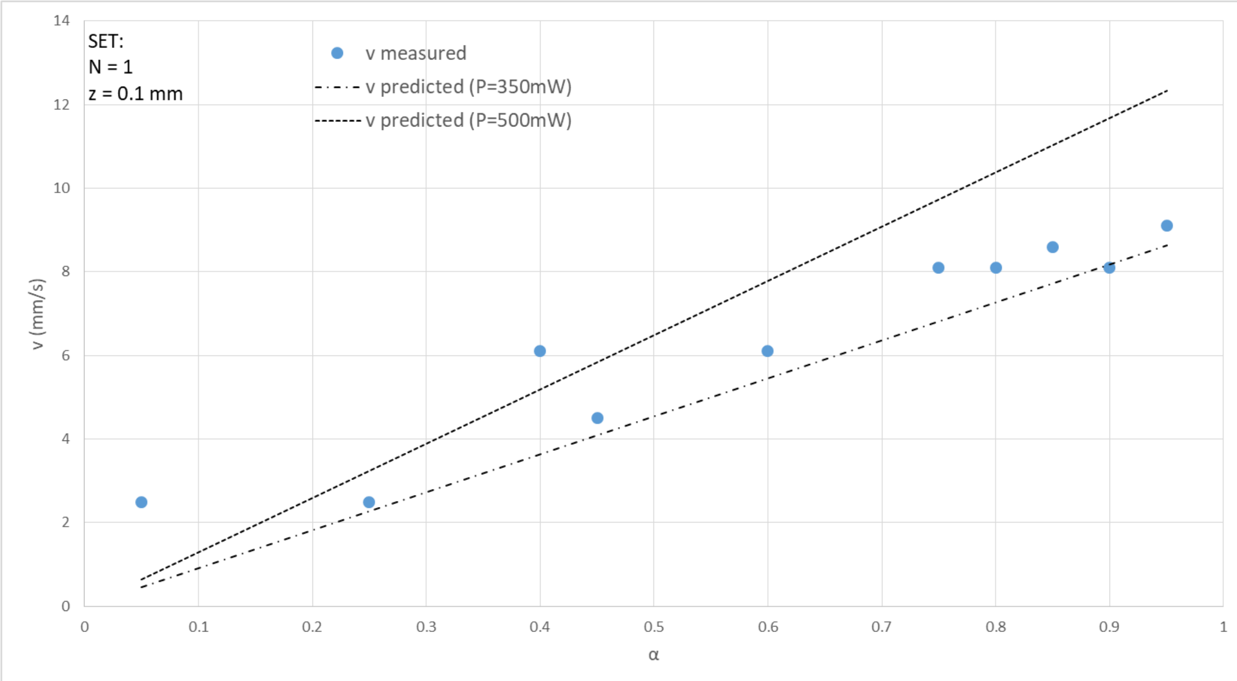

Figure 9 – Dashed lines depict upper and lower bounds of predicted cut velocity with dots representing the measured cut velocity for optimal cuts.

This comparison was made on the basis of manual for this piece of equipment states that the power output ranges from 350-500mW.[7] The measurements, however, are based on a power output of 385mW as stated on the laser engraving module. Figure 9 confirms the previous finding that white ($\alpha = 0.05$) and blue ($\alpha = 0.4$) colored paper show the most deviation from predicted cut velocity. This could be explainable as white paper reflects all wavelengths of light and blue paper reflects blue light, the color of the laser. The higher level of energy reflection could be a factor in the reason behind the larger deviation but a definitive reason cannot be concluded without a sensitivity analysis. All other colors show lower or no deviation from the predicted values.

7. Conclusions

A test procedure was designed based on laser mode TEM_{00} and heat transfer. The mathematical model to define process parameters for successful paper laser cutting was developed and experimentally verified.

1. This blue laser cutting tool was qualified by the comparison of predicted and measured cut velocity. The measured values of cut velocity were found to be within the estimated range.
2. High absorption paper colors resulted in the highest level of agreement, while white and blue colored paper diverge the most from the model. More investigation will be required to accurately model such cases.

8. Future Research

It is recommended that a sensitivity analysis be performed to collect additional statistical data and to better explain measured deviations from the model. Additional experiments taking into account a sensitivity factor could definitively conclude the reason behind the largest deviations and would lead to a more accurate model. A sensitivity value could be introduced for both absorbance and thickness to determine which variables have the largest effect on cut velocity and produce better predictions.

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