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A Method to Determine Machining Parameters for Laser Cutting Machine Using Numerical Simulation

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***Abstract*— *In laser machining process, many parameters must be considered including: laser power and cutting speed. A method based on numerical simulation has been introduced to determine machining parameters for Polymethyl-methacrylate (PMMA) on a 40W low power laser cutting machine. This method will assist machine operators to choose suitable machining parameters when cutting PMMA sheet.*

***Keywords*— *Laser CO_2, PMMA, cutting parameters, COMSOL Multiphysics.*

I. INTRODUCTION

Over the last two decades, laser machining has been employed in numerous application due to its ability to achieve rapid cutting speed, high quality cut surface, high precision, small heat affected zone (HAZ), minimal workpiece damage,… [1]. These advantages enable laser machining to be suitable for many thin nonmetallic material such as PMMA sheet, PVC sheet, wood,… Thanks to its properties such as long wave length and diffraction limits, CO_2 laser is usually favored when it comes to polymers machining [2]. According to Choudhury and Shirley (2010) [3], the quality of the cuts when machining PMMA were considerably better than those of PP and PVC.

Several parameters involved in laser machining process are laser power, cutting speed, compressed air pressure, focal point position, thickness of workpiece, thermal properties of material, ... These parameters have explicit impacts on the final quality of cutting kerfs and machining efficiency [4,5]. Many researches have been made to assess these effects and optimize the laser cutting process. Davim et al. (2006) [6] revealed based on experimental results that HAZ increase with the laser power and decrease with cutting velocity. Wang (2000) [4] presented in the results of an experimental analysis on laser cutting process of GALVABOND that low cutting speed (45 to 75 mm/min) had resulted in severe thermal damage of workpieces. He also pointed out that higher laser power and higher cutting speed produce cuts with better quality. The need for optimal cutting conditions was also raised in 2011 by Eltawahni et al. [5], when he concluded that high cutting speed might reduce cutting cost but not always improve efficiency of the process. In this paper, by experimental method Eltawahni et al obtained the optimal cutting condition to enhance quality for each thickness [5].

Recently, Giang-Nam Le et al. [7] had developed a two-dimensional numerical model to evaluate the effects of cutting parameters to the cutting kerf in laser cutting. The simulation on SUS304 showed that kerf width and depth increased when increasing laser power and kerf width decreased when increasing cutting speed [7].

This study will develop a three-dimensional numerical model based on ALE method with COMSOL Multiphysics to study the effects of laser machining parameters on PMMA. The results will be compared with experiments on a CO_2 laser cutting machine. The relationship between numerical and experimental model will be used to determine suitable cutting parameters of non-metallic material on low-power laser machine.

II. NUMERICAL MODEL

Laser machining is a thermal cutting process, laser beam directed through mirrors or fiber optics to focus on workpiece. The coherent light locally heated the work zone until the material melt or vapor. The surface reflexivity makes some of the laser energy is reflected and some is absorbed by the material. The loss of laser energy is also caused by convective heat transfer in the material surface. The heated zone instantly melts, the molten liquid is blown away by compressed air pressure forming cutting kerf. As opposed to conventional machining method, laser machining can acquire more precision than plasma, arc, ... with higher efficiency. The thermal and optical properties of the material must also be considered. Modeling the laser cutting process involved modeling laser beam heat source and material and material removal process.

A. Laser Beam Heat Source

In most laser cutting process, laser beam can be approximated as a Gaussian beam. Gaussian beam shows minimal divergence given a diameter. According to Nyon et al. [8], the heat flux cause by a Gaussian beam can be model by equation (1):

$$q(x,y) = \frac{P}{\pi R^2} A e^{-\frac{x^2+y^2}{R^2}} \tag{1}$$

Where:

P *Laser power (W)*
R *Laser beam diameter (m)*
A *Absorption coefficient (m^{-1})*

Based of Fourier's law of heat conduction, the transient temperature generated in the laser machining process of the three-dimensional model can be described in the following equation [7]:

$$\rho C_p(\frac{\partial T}{\partial t}+v\frac{\partial T}{\partial x})=\frac{\partial}{\partial x}\mathrm{k}(\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}\mathrm{k}(\frac{\partial T}{\partial y})+\frac{\partial}{\partial z}\mathrm{k}(\frac{\partial T}{\partial z})+Q_{\mathrm{int}} \quad (2)$$

Where:

k Thermal conductivity ($Wm^{-1}K^{-1}$)
C_ρ Specific heat (J kg^{-1} K^{-1})
V Velocity (m/s)
ρ Density (kg/m^3)
Q_{int} Internal heat generation rate (Wm^{-3})

As stated by [7] assuming free convective heat transfer from the surfaces of workpiece, the boundary condition to solve differential equation (2) is:

$$q_{freeconv}=h_{freeconv}(T_s-T_a) \quad (3)$$

Where:

T_s Temperature of workpiece's surface
T_a Ambient Temperature
$h_{freeconv}$ Convective heat transfer coefficient ($15\ K^{-1}m^{-2}$)

The initial condition of the model is the initial temperature of the workpiece, in this model we assume the workpiece has the temperature equal to ambient temperature 293.15 K. Numerical solving equation (2) using suitable boundary condition will give us the approximate temperature of the workpiece.

B. Material Properties

The material used in the simulation is PMMA with the chemical formula of $((C_5O_2H_8)_n)$. PMMA thermal properties is describe in Table 1. According to the phase changing diagram presented in our previous study, when the material reaches melting point of 433.15 K, there is a phase when the energy input increases when the temperature remains constant. Since liquid phase has higher internal energy than solid phase, energy must be added for solid to melt. While most of the molten material is ejected instantly by compressed air pressure making cutting kerf, some residual is left behind and solidify on the kerf.

TABLE 1. Thermal properties of PMMA [9].

Temperature (K)	Material density (kgm^{-3})	Thermal conductivity ($Wm^{-1}K^{-1}$)	Specific heat ($Jkg^{-1}K^{-1}$)	Latent heat ($kJ.kg^{-1}$)
307.75	1200	0.1922	1397.5	1.78
316.97		0.1934	1430	
326.53		0.1955	1470	
332.43		0.1966	1510	
345.13		0.1979	1580	
352.65		0.1986	1600	

C. Laser Cutting Process

Assuming the heat flow is one-dimensional and heat conduction close to zero, the internal energy of removed material is used to calculate the speed of the fusion process. In previous research [7], the laser beam width was considered constant during cutting process. This research will take in to consideration the evolving beam width. Assuming the beam propagate through z direction in free space, the evolving spot size along z axis is determine by equation (4) [10]:

$$w^2(z)=w_0^2[1+(\frac{\lambda z}{\pi w_0^2})^2] \quad (4)$$

Where:

w_0 beam diameter at focal point
λ wave length of laser

The energy required to melt the material considering the evolving beam width is:

$$E_m=\rho\left[C_p(T_m-T_a)+L_f\right]\int_0^{v_m\cdot t}\frac{\pi}{4}[1+(\frac{\lambda z}{\pi w_0^2})^2]\,dz \quad (5)$$

Where:

E_m Energy to melt material (J)
ρ Density ($kg\ m^{-3}$)
w_0 Laser beam waist (m)
C_ρ Specific heat (J kg^{-1} K^{-1})
L_f Latent heat of fusion (Jkg^{-1})
T_m Melting temperature (K)
T_a Ambient temperature (K)
v_m Melting velocity (ms^{-1})
t Time (s)
λ Laser wavelength (μm)

III. SIMULATION

A. Simulation Model

Numerical simulation is becoming more and more vital in science and engineering. Computational science and engineering evaluate new products but also develops and optimizes design and manufacturing process. COMSOL Multiphysics is a very powerful software for solving Multiphysics problems like laser cutting process.

The model uses the Arbitrary-Lagrangian–Eulerian method (ALE method) to simulate the melting surface. When the surface is heated and reach the energy to melt material E_m, a deformed velocity is applied. The ALE method has the advantages of being able to simulate great distortions of the melting surface and still have a good resolution [11].

In the simulation, the Free Tetrahedron Mesh is created with the minimum elements size of 2.5×10^{-5} mm. The front and the top of the workpiece have more dense mesh since this is the deformed surfaces.

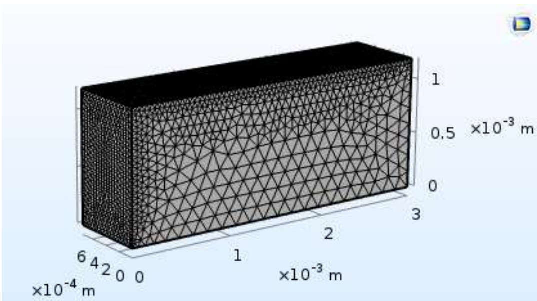

Fig. 1. Workpiece meshing.

The simulation is modeled with a 18W CO_2, to reduce the computation workload, a symmetry plane is used so that only

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half of the workpiece must be computed. The laser machining process is simulated with heat flux moving x-direction at four different cutting speeds from 1 m/min to 4 m/min.

The boundary condition for Heat Transfer in Solid is free convective heat transfer from all surfaces of the workpiece. The boundary condition for deformed geometry is zero displacements at the bottom surface and only displacement along Z axis with all side surfaces. The initial condition of the workpiece is that all surfaces preliminary temperature is equal to ambient temperature 293.15 K.

B. Simulation Results

The simulation results show the shape of heat affected zone after the cutting process Fig. 3, Fig. 4. The cutting process involves 2 stages. In the first stage, the kerf cannot reach final cutting depth since in this stage workpiece doesn't receive enough laser power. In the second stage, the cutting depth kerf and reach the final depth. To reach uniform cutting depth, the workpiece must be preheated or cutting speed at first stage of the process must be calculated to normalize the energy absorption of the workpiece. When simulation on a 18W CO_2 laser machine, the results show clear reduction in kerf width when increasing cutting speed gradually from 1 m/min to 4 m/min. The relationship between cutting speed and cutting kerf width is showed in Fig. 6, Fig. 7.

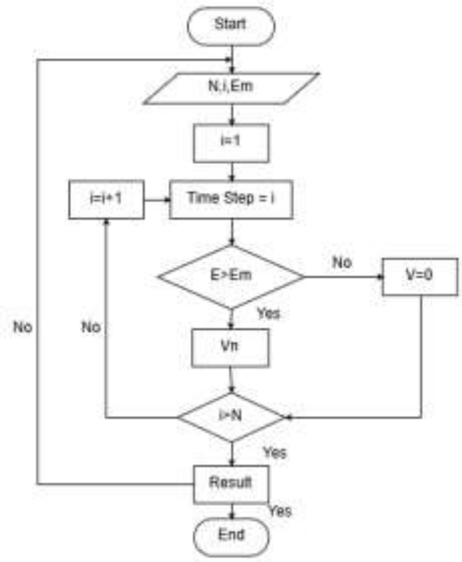

Fig. 2. Computational method.

Where:

N	Computational steps
T	Workpiece temperature
Vn	Melting speed
Em	Energy to melt material.

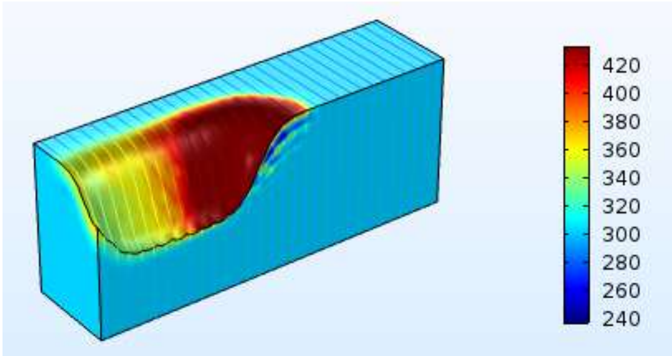

Fig. 3. 3D view of temperature distribution in workpiece at laser cutting speed of 4m/min.

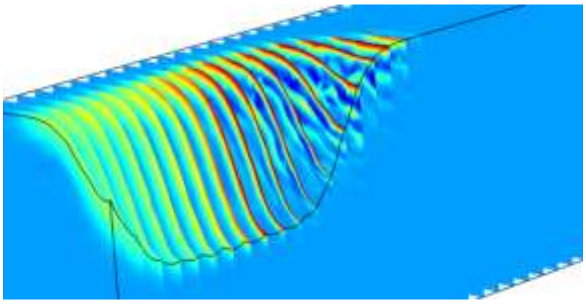
Fig. 4. Sliced view of workpiece after cutting process.

IV. EXPERIMENTAL ANALYSIS

Apart from computational analysis, an experimental analysis is also conducted on a CO_2 laser cutting machine designed and manufactured by VIMESGROUP. Experimental laser power is 18W, experimental speed is 1 m/min to 4 m. The cutting kerf width is measured and evaluated.


Fig. 5. Experimental machine.


Fig. 6. Experimental results.

The relationship between experimental and computational results is shown in the graph below.

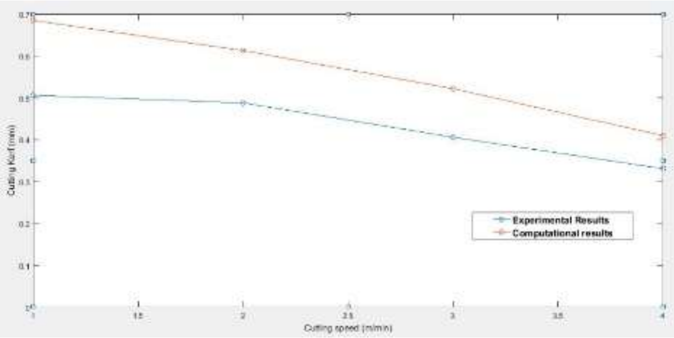

Fig. 7. Comparison of computational and experimental results.

V. RESULTS AND DISCUSSION

The laser cutting process of PMMA sheet was simulated with COMSOL Multiphysics using ALE method. The laser source was considered Gaussian-distribution heat source. The molten material ejection was modeled using ALE method. From figure 3, the computational result shows when machining at the same laser power the cutting kerf width reduce when we increase cutting speed steadily from 1 m/min to 4 m/min. The experimental and computational results follow the same trend while the computational cutting kerfs are bigger then experimental kerfs. There are differences when comparing computational and experimental results due to the loss of laser power through optical system. A coefficient for the machine in simulation process is proposed to balance this loss.

The computational results can be used by machine operator to select suitable cutting parameters. This method should be used to evaluate cutting parameters and create database for various material.

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