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COMPARATIVE ASSESSMENT OF EXPERIMENTAL AND NUMERICAL SIMULATION OF ABLATION DEPTH IN PMMA MULTIPASS LASER CUTTING

Abdulhafiz A. SHAIKH, Md Azharuddin ALI, Aakif ANJUM

Abstract: *In the present work, the simulation of multi-pass laser cutting on PMMA has been investigated in Abaqus by considering script for variation in Gaussian distribution of energy. Ablation depths were predicted at each pass during laser cutting at Power 30 W and 55 W with cutting velocity at 20 mm/sec. It was observed that Ablation depth increases with the increase in power and number of passes at a constant speed. The simulation results have been compared with the experimental results. It was found that the deviation occurred in the range of 10% to 32% due to energy applied in actual cutting and assumption applied in script for specific energy concept towards deletion of element for visualizing cutting depth.*
Key words: *Laser, Simulation, Ablation depth, multi-pass, Laser power, cutting speed*

1. INTRODUCTION

Laser cutting is an unconventional machining process which deals with the thermal cutting of materials used in conjunction with the production process.

Cutting material can be removed by melting, vaporization or blown away using jet. Different types of lasers which are present in the market are CO_2 Laser, Solid-state (Nd: YAG) laser and fiber laser [1]. CO_2 Laser has been widely used in industrial and research application [2]. It is very effective and precise with high degree of accuracy and high-quality surface finish [3,4].

Previously, many researches have been done using commercial finite element analysis (FEA) software [4-7]. Nath et al. [5] made the observation from the results of numerical simulation that with the increase of laser power, ablation depth has increased. Liu et al. [9] investigated the cutting of carbon fibers by laser by varying different parameters of both the carbon fibers and the cutting machines.

They analyzed the obtained characteristics of carbon fiber cut and also compared them with the ones obtained by the conventional cutting process by sawing. Negarestani et al. [10] investigated the numerical simulation, based on ‘element death’ technique, of laser machining of CFRP. Carbon fiber reinforced composites (CFRP) is a heterogenous fiber-matrix mesh composite used in aerospace and automotive industries for its high demand of being efficient and low-cost machining process.

Chen et al. [11] studied the laser induced mechanism of SiCf/SiC composites and the link between the laser parameters (scanning speed and scanning spacing) and depth of cut based on the photoelectric effect phenomenon.

Shena et al. [12] elaborated a mathematical modelling of laser cutting of Aluminium, Titanium, Copper, Silver and fused quartz. The effects on melt depth due to power density, temperature profile and time evolution are evaluated by analytic method.

Yilbas et al. [13] investigated the simulation of temperature and stress field in the cutting section using FEM and analysed the residual stress generated on a thick sheet metal during laser cutting operation. It is concluded after analyzing the result, that temperature and stresses increase rapidly in the cutting zone, especially in the direction perpendicular to the force applied.

M. Radovanovic and M. Madic [3] reviewed the experimental investigation on cutting quality characteristics of CO_2 laser with analyzing different process parameters. They found the optimal cutting parameters by statistical and regression analysis. Chryssolouris et al. [14] analytically established a model to calculate groove depth based on process factors and thermal properties of multiple composite materials. Jiao et al. [15] investigated the influence of laser process parameters (laser power, cutting speed and specimen geometry) on crack propagation in glass, used in flat panel display industries, through numerical simulation by finite element analysis software (ANSYS). To reduce the thermal stress developed in direct cutting and avoid fracture of glass, dual CO_2 laser beams were used. Ghoochani et al. [16] investigated about the comparative assessment between numerical simulation and experimental work of pulsed CO_2 laser-induced micro-channel on poly-ether sulfone (PES) polymer. The experimentation is done by consequent pulses with different scanning speed and the results were compared with the simulation.

In the earlier study, the simulation of multi pass approach is rarely attempted [17-22]. The present work deals with simulation of laser cutting process using Abaqus using multi-pass approach to estimate the effects of laser cutting parameters on depth of cut by varying laser power at a constant speed. The comparative assessment of the experimental and simulated micro channel depth is presented in this work.

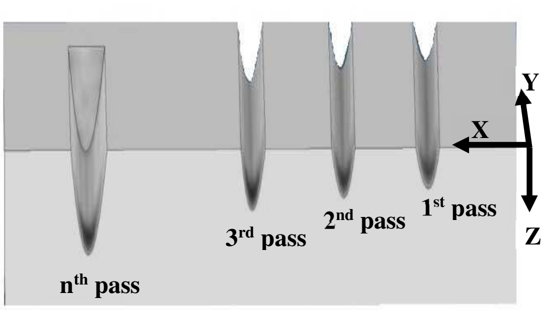


Fig. 1. CAD Model to show multipass laser cutting process.

2. NUMERICAL METHODOLOGY

2.1 CAD Model

The concept of laser cutting process simulations is visualized as shown by CAD Models in figure 1. Laser beam is considered to be moving with the cutting velocity "v" in the Y-direction and thickness of the sample is taken in Z-direction. The figure 1 represents the multipass laser cutting process from 1st pass to 2nd to 3rd and up to nth pass.

2.2 Initial and Boundary Conditions

In the present model, the initial temperature of the sample is considered at room temperature i.e., 298 K. The laser beam is transmitting body heat flux through conduction from top surface to bottom. It is assumed that apart from top and bottom surfaces, rest of the surfaces are adiabatic. The top surface has heat convective loss due to assistant gas where surface film coefficient is taken as 3000 W/mm·K, while at bottom surface, heat loss is due to natural convection and the value of surface heat transfer coefficient is taken as 30 W/mm·K. Radiation losses are considered on both surfaces with emissivity value as 0.05 [23-25]. The sink temperature is set at 298 K.

2.3 Numerical Simulation

The depth of cut or the groove generated on the substrate while laser cutting operation is the ablation depth. The simulated results are shown in the figure 2 and the ablation depth at different multiple passes are estimated at keeping constant power of 30 W and cutting velocity 20 mm/sec. Here, d1 is represented as the ablation depth for first pass, while d2 for second, d3 for third and d4 for fourth pass. It is observed that the ablation depth increases with the increase in number of passes. $d1<d2<d3<d4$.

Similarly, next simulation is done for the second setup, where power is changed from 30 W to 55 W by changing the power in the subroutine code and feeding in the FEM software. The simulated results are attained by keeping constant laser power of 55 W and cutting velocity 20 mm/sec and the ablation depth at different multiple passes are estimated.

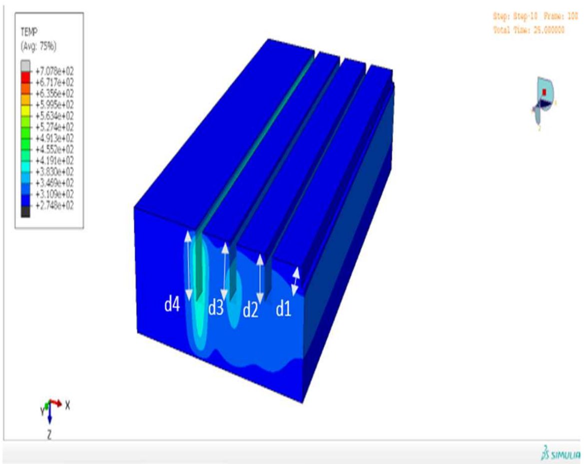


Fig. 2. Simulation result of ablation depth in multiple passes at (P=30 W, v= 20 mm/s).

The outputs are shown in the figure 3. Here, D1 is represented as the ablation depth for first pass, while D2 for second, D3 for third and D4 for fourth pass. The trend of the results illustrates that depth increases with the increase in number of passes, D1<D2<D3<D4.

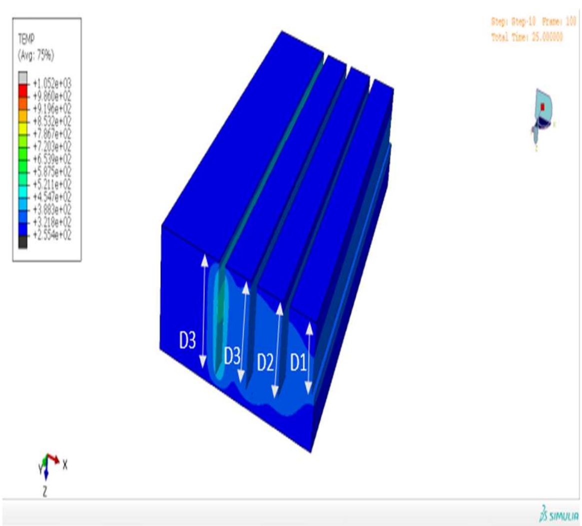


Fig. 3. Simulation result of ablation depth in multiple passes at (P=55 W, v= 20 mm/s).

3. EXPERIMENTAL VALIDATION

Simulated results obtained in the output database of the FEM software has been recorded and validated with the present experimental values of the depth of cut at each pass of laser cutting operation. Two samples of transparent casted PMMA were taken of dimensions (25 mm x 20 mm x 10 mm) having thickness of the sample as 10 mm. CO_2 laser has been used for continuous cutting of multiple laser passes. The experiments are designed considering OFAT (one factor at a time) in which lower level of laser power is set at 30 W for first sample and higher level of laser power is 55 W for the second sample with the constant laser cutting speed of 20 mm/sec. For the ejection of molten material during laser cutting, different assist gases like nitrogen, oxygen, argon, and compressed air are utilized. The gas purity and assist gas pressure range also affect how well the laser machine cuts [4,26–30]. In order to remove the melts from the working area and achieve melts-free depth, the air pressure functions as an assist gas. Throughout the experiment, a constant 3 bar air pressure is maintained. For the initial cut of all specimens, the focus distance between the nozzle and the top of the workpiece is maintained constant. The focal distance, which is determined by adding the amount of material that was eliminated in the first pass and the original focus distance, varies for the second pass.

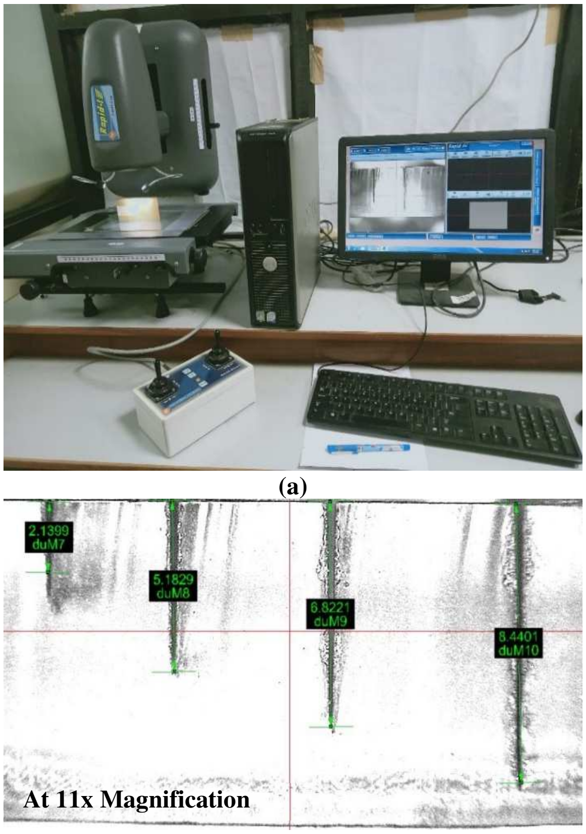
The material properties of PMMA substrate are considered in table 1 [31].

Table 1

Material properties of PMMA.

S. No	Characteristic	Units	Value
1	Thermal conductivity	W/mmK	$0.19 \cdot 10^{-3}$
2	Specific heat	J/kg/K	1477
3	Density	kg/mm³	$1.18 \cdot 10^{-6}$
4	Emissivity	-	0.91
5	Absorptivity	-	0.95

Rapid-I software is used for measuring the dimension of ablated depth which is shown in figure 4(a). Magnification was set to 11x, profile light was set to 30%, then Z-axis is adjusted to focus the vision for measuring the distance between the cuts. Then line command is chosen to draw a two vertical lines along cut width. After that using measure command, distance between two lines is measured. Using this procedure all samples were measured. The microscopic image of ablated depth at power 30 W and speed 20 mm/sec is depicted in figure 4(b).



(a)

(b)

Fig. 4. (a) Vision measuring machine (Rapid-I), **(b)** Ablation depth at P= 30 W, v=20 mm/s

4. RESULTS AND DISCUSSIONS

Numerical analysis of two different cases have been arranged. Sample 1 and Sample 2 are modelled at laser power 30 W and 55 W respectively with keeping constant laser cutting speed at 20 mm/sec.

Experimental results have been attained and shown in the previous section. Difference between the value is observed as the mean error and percentage error is calculated by equation 1. The simulated results are compared with experimental results.

$$\text{Error} = \left|\frac{\text{Experimental result}-\text{Simulated result}}{\text{Experimental result}}\right| \times 100\ \% \quad (1)$$

Comparative assessment is done between the simulated results and experimental results as shown in the table 2. In the first pass, simulated result gives 1.5 mm as the depth of cut while experimental results give 2.13 mm. In the second pass, simulated result gives 3.5 mm as the depth of cut while, experimented value is 5.18 mm and in third pass, simulated result shows 5 mm as the ablation depth while, experimental value is 6.82 mm. At fourth pass ablation depth in simulation gives 6.5 mm as an output, while calculated experimental value is 8.44 mm. The depth of cut measured and simulated have been compared and relative error is found between 22.98% to 32.41%.

Table 2

Comparison of simulated and experimental ablation depth for P= 30 W, v=20 mm/s.

Sample 1	**Power (W)**			**Cutting Velocity (mm/sec)**
	30			**20**
No of passes	Ablation depth (simulated) in mm	Ablation depth (experimental) in mm	|Error|	% Error
1st	1.5	2.13	0.63	29.57
2nd	3.5	5.18	1.68	32.41
3rd	5	6.82	1.82	26.68
4th	6.5	8.44	1.95	22.98

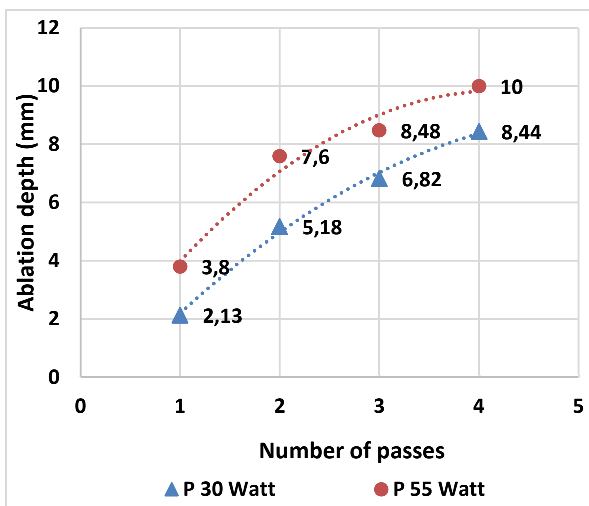


Fig. 5. Experimental results of ablation depth in multiple passes at (P=30 W & 55 W)

Comparative assessment is done between the simulated results and experimental results as shown in the table 3. This is observed that in the first pass, simulated result gives 3 mm depth of cut, while experimental results give 3.80 mm. In the second pass, simulated result gives 6.5 mm depth of cut while, experimented value is 7.60 mm and in third pass, simulated result shows 7.5 mm as the ablation depth while, experimental value is 8.48 mm.

Table 3

Comparison of simulated and experimental ablation depth for P= 55-W, v=20 mm/s.

Sample 2	**Power (W)**		**Cutting Velocity (mm/sec)**	
	55		**20**	
No of passes	Ablation depth (simulated) in mm	Ablation depth (experimental) in mm	|Error|	% Error
1st	3	3.8	0.8	21.05
2nd	6.5	7.60	1.1	14.47
3rd	7.5	8.48	0.98	11.55
4th	9	10	1	10.00

At fourth pass ablation depth in simulation gives 9 mm as an output, while calculated experimental value is 10 mm which is a through cut of the material. The depth of cut measured and simulated have been compared and relative error is found between 21.05% to 10%. The percentage error in both the cases of laser cutting having laser power 30 W and 55 W at cutting velocity of 20 mm/sec is analyzed and the amount of error is found between range of 10% to 34%.

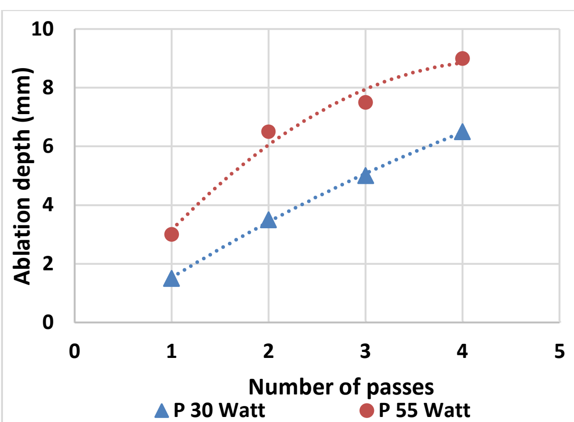


Fig.6. Simulated results of ablation depth in multiple passes at (P=30 W & 55 W).

From figure 5 and 6, it can be visualized that the same trend is followed in experimental value as well as simulation results. The graph clearly demonstrates that the ablation depth is increasing with the number of multiple passes for a given set of power. This can be seen that the ablation depth also increases with the increase of laser power at particular pass. Similar trend is observed with the results mentioned in [16, 31,32].

5. CONCLUSION

The CO_2 laser micro channeling on polymethylmethacrylate has been simulated considering moving heat source concept. The effect of laser cutting due to multiple passes on ablation depth is studied at power 30 W and 50 W at a constant speed of 20 mm/s. From the analysis discussed above, the conclusions are derived as below:

- In the first pass the depth of cuts are observed 1.5 mm and 3 mm for 30 and 50 W laser power.
- In second pass due to Gaussian beam energy distribution the depth of cuts obtained for 55 W is 200% of the first pass.
- While the depth of cut for the third and fourth passes are 232% and 263% of the first pass at 55 W and 320% and 396% of the first pass at 30 W.
- It is noted that depth after each pass do not directly multiply but variation depends upon varying energy due to changing focus distance at each pass, this is due to the amount of energy available to remove the material gets reduced as focal distance gets increased from the top surface of the work piece.
- The pattern of variation for ablation depth for the number of passes is obtained through experimental and simulation is almost same.
- However, the deviation observed in the ranges of 22.98% to 32.41% for 30 W at 20 mm/sec and in the range of 10% to 21.05% for 55 W and 20 mm/s.
- Thus, the laser material interaction and ablation of PMMA by considering Gaussian moving heat source has been modelled with the concept of element deletion applied through user defined script in FEM software.

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EVALUAREA COMPARATIVĂ A REZULTATELOR EXPERIMENTALE ȘI ALE SIMULĂRII NUMERICE PRIVIND ADÂNCIMEA CANALULUI LA TAIEREA CU FASCICUL LASER ÎN MAI MULTE TRECERI A PROBELOR DIN PMMA

În lucrarea de față, a fost investigată simularea tăierii cu laser din mai multe treceri a unor probe din polimetilmetacrilat (PMMA) folosind softul Abaqus și luând în considerare un scenariu de variație gaussiană a distribuției energiei. A fost estimată valoarea adâncimii canalului pentru fiecare trecere în procesul de tăiere cu un fascicul laser având puterea de 30 W și respectiv de 55 W și cu o viteză de tăiere de 20 mm/sec. S-a observat că adâncimea canalului crește o dată cu creșterea puterii fasciculului și a numărului de treceri, la o viteză constantă de tăiere. Rezultatele simulării au fost comparate cu rezultatele experimentale. S-a constatat că a apărut o o diferență de ordinul a 10% până la 32% între rezultate, datorită diferenței dintre energia specifică utilizată în condițiile propriu-zise de tăiere și cea presupusă a fi aplicată conform scenariului ce ia în considerare adâncimea canalului.

Abdulhafiz A. SHAIKH, Professor, PhD, S.V. National Institute of Technology, Department of Mechanical Engineering, aas@med.svnit.ac.in, CAD LAB SV NIT, Surat, India.

MD AZHARUDDIN Ali, M. Tech, S.V. National Institute of Technology, Department of Mechanical Engineering, p20cc024@med.svnit.ac.in, CAD LAB SV NIT, Surat, India.

Aakif ANJUM, Doctoral Research scholar, S.V. National Institute of Technology, Department of Mechanical Engineering, anjumaakif@gmail.com, CAD LAB SV NIT, Surat, India.