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Finite Element Simulation of Laser-Micromachining

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***Abstract*— Finite element models were developed to simulate laser-micromachining of acrylic sheet. Different material models and process parameters were considered in simulations. Temperature plots generated by various simulations were compared and discussed. The important factors in finite element modeling to realistically simulate laser-micromachining were highlighted. Simulated results show consistently with the expected laser machining mechanism.**

***Index Terms*—Finite Element Modeling, Laser-micromachining, CO2 laser**

I. Introduction

Increasing demands in MEMS fabrication are leading to new requirements in production technology. Laser-micromachining has many technological advantages compared to conventional technologies, including design flexibility, production of complex shape and possibility of rapid prototyping. It has demonstrated its potential in convenient fabrication of microstructure as it can be integrated into CAD/CAM system. However, in order to carry out the process in CAD/CAM system, appropriate testing of the process virtually is important. As such, the use of finite element (FE) modeling and simulation is the right tool to meet the requirement. Adequate prior simulations are mandatory to save time and cost of real production [1-6].

Several types of laser have been tried out for micromachining in the past study. Some of them are excimer laser, femtosecond laser and solid state laser. All these lasers have very short wave length and pulse duration as the shorter they are the smaller the feature size is realizable. Excimer laser, for instance, has a wavelength operating in UV region (193-308 nm) with average power of 100W, and typical pulse duration of 20 ns. There are numerous parameters involved in laser processing. Laser repetition rate, pulse duration, beam intensity, and moving velocity if the laser needs to create a designated geometry are important process parameters. The excimer laser and femtosecond laser were successfully utilized in laser-micromachining of silicon for MEMS components [7-9].

Machining mechanism may depend on the type of material being machined. Major mechanisms are melt transition when cutting metals, vaporization especially with silicon and polymers, and stress cracking when processing glass. Considerable amount of research has been reported in the past on laser machining centering on replacing conventional machining where machining dimensions are in mm range [10-12]. Experimental work of laser-micromachining of silicon was reported by [7-9]. In their report, machining mechanism and on the effect of process parameter on surface finish were comprehensively presented. Details can be found in [7-9]. In brief, computational model and simulation of this process has been lacking while it can be helpful to predict appropriate process parameters that make high quality products. In this research, simulation of laser-micromachining using finite element method was presented. This technique would be another option to overcome the difficulties encountered in making the micro-size products as well as time and cost-prohibited situations.

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II. Finite Element Model

Basically, two FE models – (1) without convection heat transfer and (2) with convection due to surrounding air and cooling gas - were developed. Due to limited space, related theoretical background was omitted, which can be found in [13-15]. Figure 1 describes the schematic of FE models used for simulating laser micromachining. Transient heat transfer analysis was chosen to predict time-resolved temperature distribution in the material due to laser pulse. Material for laser processing was acrylic and computational domain was narrowed down to 1x0.5 mm^2. The thickness was assumed to be 1 mm. Necessary material properties were taken from built-in material library available in the FE package. Material model considered were isotropic and phase change material models. The element type was plate element.

The most important part of the FE modeling was mesh design including the nodal distance along the laser path and node order as the laser would follow these. Figure 2 shows the FE models as a whole and close-up view of where finer mesh was designed for laser path. As a straight cut would be simulated, it was essential that certain nodes in the computational domain would follow a straight path as depicted Figure 2. The nodal distance along the laser path was modeled to be the length of 10 um each. This length was in accordance with the laser repetition rate and moving velocity along the designated path assuming CO2 laser with moving velocity of 1 mm/s was used. Laser beam was represented by nodal heat flux and activation time which was defined consistently with load curve. Laser power was defined based on the frequency and moving velocity. Laser moving velocity was controlled by nodal distance and activation time. Surface convection heat coefficient was assigned to include convection heat transfer due to surrounding air. Similarly, convection effect of cooling gas was included by assigning very high convection coefficient near the laser path. Initial nodal temperature was assigned to be at 25C assuming the laser processing at room temperature.

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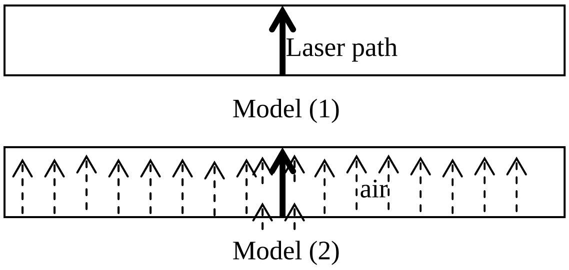

Figure 1 Schematic of FE models

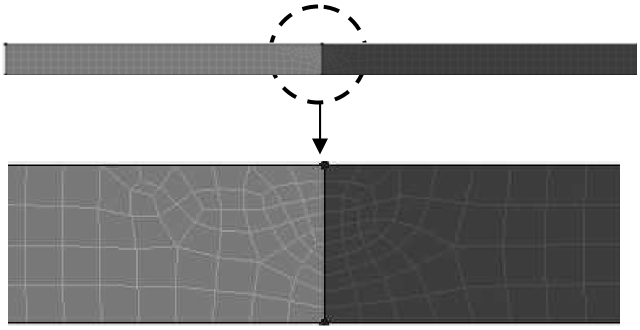

Figure 2 Mesh design

III. FINITE ELEMENT SIMULATION

Table 1 shows total number of simulations done. Important parameters in laser processing are laser power and moving velocity. In fact there are numerous parameters involved in FE modeling itself. However, due to limited space and time, only few parameters were varied in those simulations. In simulations 1-3, same material model of isotropic type and process parameters were modeled. The major difference in these simulations was that no convection heat transfer in 1, presence of surrounding air in 2 and presence of surrounding air plus cooling gas in 3. Then simulation 4 and 5 varied process parameters such as moving velocity and laser power while keeping other parameters constant. In simulation 6, phase change material model was incorporated into FE modeling with other parameters being same as 3.

Table 1 Number of simulations

No.	Description
1	No convection at all
2	Repeat 1 with convection due to surrounding air
3	Repeat 2 with convection due to cooling gas
4	Repeat 3 with different laser moving velocity
5	Repeat 3 with different laser power
6	Repeat 3 with phase change material model

IV. SIMULATED RESULTS

Figure 3 shows relative temperature contours generated by simulations 1-3 respectively. Convection heat transfer due to surrounding air seemed to be not effective as no appreciable difference between results of 1 and 2 was seen. Absence or presence of surrounding air did not change the temperature distribution in the processed material. However as evidence, the remarkable effect of presence of cooling gas was revealed. Indeed, it cooled down the material in almost one order less temperature.

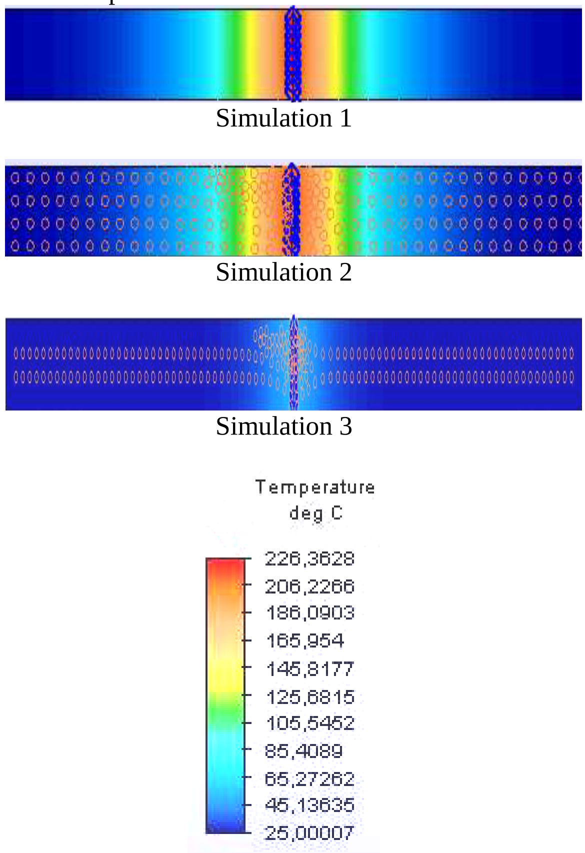

Figure 3 Temperature contours simulated for including and excluding convection

Figure 4 shows temperature contours when the process parameters were changed. The effect of increased laser power was more dominant than that of increasing velocity on the temperature gradient. This also indicated that shorter time of the laser meeting the material surface was preferable.

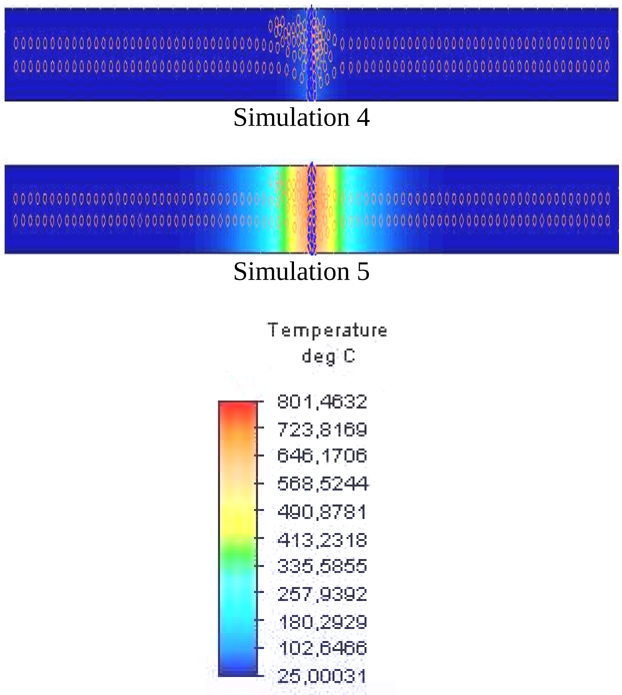

Figure 4 Temperature contours simulated for changing process parameters

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Figure 5 demonstrates the temperature distribution simulated by incorporating phase change material model. The advantage of using this material model was that the state of phase change during laser processing was predictable. As illustrated in Figure 6, localized phase change due to laser beam-material interaction can be seen clearly.

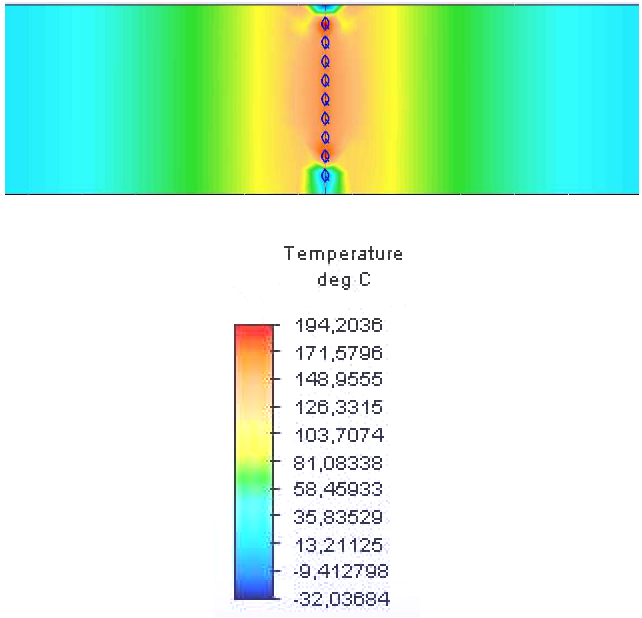

Figure 5 Temperature contours simulated with phase change material model

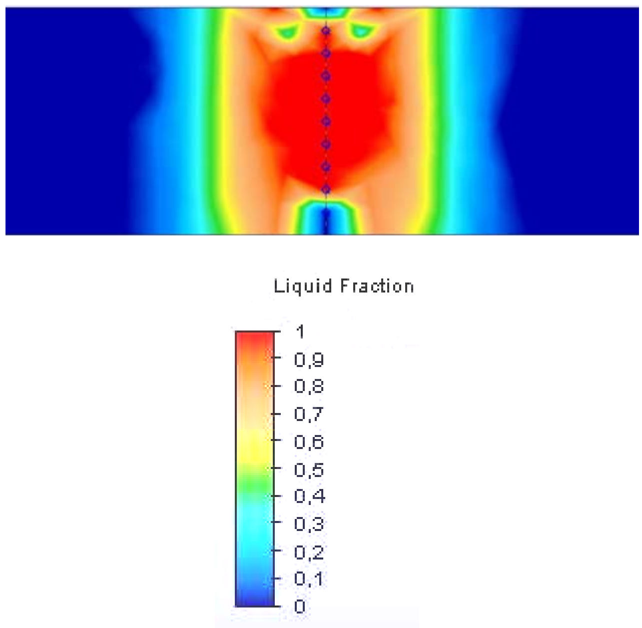

Figure 6 Phase change condition in the material

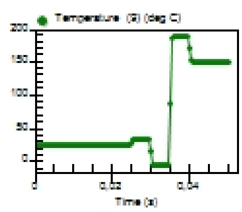

Figure 7 Temperature plot indicating phase change in the material

V. CONCLUSIONS

Finite element simulation has been successfully carried out for simulating laser-micromachining of acrylic material. With reference to the simulated results, proper compromise between the laser power and moving velocity would be essential in order to produce defect-free edges in efficient processing time.

The important factors for realistic simulation of laser-micromachining were found as appropriate material model, accurate thermal properties of material under processing, and mesh design in finite element modeling. Material model and boundary condition used strongly affected the simulated results.

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