Simulation of Laser Structuring by Three Dimensional Heat Transfer Model

Bassim Bachy, Joerg Franke

Abstract—In this study, a three dimensional numerical heat transfer model has been used to simulate the laser structuring of polymer substrate material in the Three-Dimensional Molded Interconnect Device (3D MID) which is used in the advanced multi-functional applications. A finite element method (FEM) transient thermal analysis is performed using APDL (ANSYS Parametric Design Language) provided by ANSYS. In this model, the effect of surface heat source was modeled with Gaussian distribution, also the effect of the mixed boundary conditions which consist of convection and radiation heat transfers have been considered in this analysis. The model provides a full description of the temperature distribution, as well as calculates the depth and the width of the groove upon material removal at different set of laser parameters such as laser power and laser speed. This study also includes the experimental procedure to study the effect of laser parameters on the depth and width of the removal groove metal as verification to the modeled results. Good agreement between the experimental and the model results is achieved for a wide range of laser powers. It is found that the quality of the laser structure process is affected by the laser scan speed and laser power. For a high laser structured quality, it is suggested to use laser with high speed and moderate to high laser power.

Keywords—Laser Structuring, Simulation, Finite element analysis, Thermal modeling.

I. INTRODUCTION

RECENTLY, laser structuring applications has received an increasing attention for a wide variety of applications such as medicine, industries and the others fields due to its excellent quality with high productivity and flexibility. In this process, main variable parameters are power of laser beam (p) and laser beam diameter (d), this laser beam moves with velocity (v) and directed onto the surface of a work piece, see Fig. 1 which shows a simple schematic for the laser process.

One of the most important applications for this laser process is the laser activation or structuring process in manufacturing electronic substrates.

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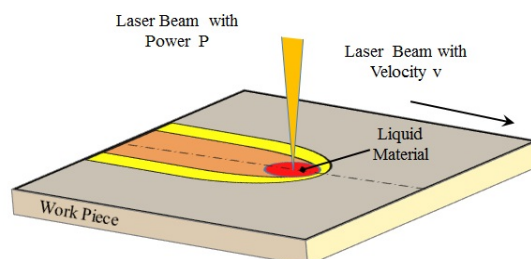
Fig. 1 Simple schematic for the laser process

As this substrates or devices to be structured could be in miniaturized forms, there is a necessity to use finer and more accurate tools in producing finest structures, where by this tool we can remove materials from the surfaces with very high accuracy and with high quality. The high accuracy for the laser which is approximately less than ±25µm make it suitable for the three-dimensional injection molded substrates or 3D MID structures [1]. This process includes three steps which are injection molding, laser structuring and followed by metallization for conductive patterns. In fact this process is similar to the laser cutting or laser welding process; the main differences are in the laser parameters such as power and speed used during the process. Improper use of the laser parameters leads to production of low quality products with high defect percentage. This can be damage of the neighboring structures or interference with each other especially in the very fine circuitry or micro devices. For process control and defining an optimal process window, it's very important to understand the effect of each parameter.

Little research has been devoted to understand the relationship between the laser parameters and the quality of the final product. But many studies have been carried out to simulate the laser welding and cutting by various mathematical models supported by experimental work for different materials.

A simulation and optimization of continuous laser transmission welding (LTW) validated with experiments is investigated by Xiao Wang et al. [2], in this work a mathematical model have been used to simulate the laser welding process for the dissimilar materials as well as experimental work was carried out to make a verifications from the result of this model. Sanjay Mishra et al. [3], carried out a 2D mathematical modeling for the laser drilling process for the nickel-based super alloy sheet using Nd:YAG laser also in this work an equations have been used to calculate the hole diameter and temperatures distributions. Finite element simulation of laser transmission welding of dissimilar materials between polyvinylidene fluoride and titanium was

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carried out by Bappa Acherjee et al. [4], a three-dimensional finite element thermal model is developed to simulate the laser transmission welding process for joining polyvinylidene fluoride with titanium using a distributed moving heat flux. The objectives of this study were to predict the transient temperature field.

Junjie Ma et al. [5] were propose a three-dimensional (3D) finite element (FE) model is applied to predict the temperature evolution in the laser welding of galvanized high-strength steels in a zero-gap lap joint configuration. Also the effects of the laser welding parameters on the zinc-coated vaporized area and the steel weld pool area have been study in this paper.

In this work a three dimensional numerical heat transfer model based on finite element method FEM has been proposed to simulate the laser structuring process. The transient temperature fields are obtained through thermal solution performed by using APDL (ANSYS Parametric Design Language) provided by ANSYS [6]. From this model the temperatures distributions as well as the depth and the width of the groove metal which is removed from the surface of the work piece can be predicted. Also this work consist of experimental work to study the relationship between the laser parameters such as laser scan speed and the laser power with the depth and width of the groove metal which is removed from the surface of the work piece. The comparison between the experimental and the theoretical results show good agreement.

II. THEORETICAL WORK

A. The Proposal Model

As mentioned previously, laser process in this work is similar to thermal cutting process. The work piece is heated locally by the laser beam which moves with velocity (v) focused onto the surface of the work piece as shown in Fig. 1. The material absorbs some of the laser energy and the rest of the energy is reflected. The absorbed laser energy is transferred to the material by thermal conduction in the three dimensions. By this energy, a phase transformation takes place from solid to liquid and then to vaporizes starting at the surface of the metal and this is depends on the parameters such as thermal material properties, laser parameters and the initial temperature of the work piece.

Equation (1) is the most common formulation considering laser process thermal evolution as a heat transfer process utilizing Fourier heat conduction theory [4], [5]. Xiao Wang et al. [2], used this equation to describe the governing heat conduction in the moving medium but the mean different is that there is only one movement for the laser beam and the work piece is fixed.

This equation describes the general heat conduction equation for the temperature *T* as a function of *x, y, z* and time *t* is, [2], [4], [5] the main assumptions in this proposal model are as follows:

1. Laser beam profile is assumed to be Gaussian and constant along the *Z* direction.

2. The material density does not vary with the temperature, and the sheet material is homogeneous and isotropic in nature.

$$\frac{\partial}{\partial x}\left(kx\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(ky\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(kz\frac{\partial T}{\partial z}\right) + q(x,y,z,t) = \rho cp \frac{\partial T}{\partial t} \quad (1)$$

where *T* is the transient temperature in Kelvin at (x , y, z, t), t is the time in sec, *kx, ky,* and *kz* are the thermal conductivities in the *x, y* and *z* directions (in W/m-K), ρ is the density of the material (kg/m^3), *cp* is the specific heat (in J/kg-K), x, y, z are the coordinate axes and $q(x,y,z,t)$ is the rate of the internal heat generation per unit volume (W/m^3).

B. Heat Input

The laser beam is radially symmetric with a Gaussian heat flux profile. Equation (2) can be used to calculate the amount of heat flux as a function for 'R' which is refer to the distance from the beam center, [4], [5], [7]-[9].

$$q(R) = \begin{cases} \frac{2P}{\pi r^2}ex\left(-2\frac{R^2}{r^2}\right) & \text{For} \quad R \le r \\ 0 & \text{For} \quad R > r \end{cases} \quad (2)$$

where P is the laser power, r is the beam radius in m; R is the radial distance from the beam center in m.

C. Boundary Condition

Initially (t = 0), the work piece at the initial condition with temperature 27°C (300 K) which is equal to the ambient temperature T_{amb}. Also the amount of q(R) which is refers to the input heat from the moving laser beam is equal to zero. When the laser process starts (t > 0), the amount of q(R) increases and by using (2), the heat flux or the temperature of the work piece will increase to $T_{S.W}$, so that and due to the difference in the temperature between the boundary of the work piece and ambience a heat transfer takes place from the surface of the work piece to the ambience. In fact all the surface of the work piece except the bottom transfers heat to the ambiance by two types of heat losses which are as follow:

1. Heat Transfer by Convection

The amount of heat loss by convection (q$_c$) from the surface of the work piece is given by (3)

$$q_c = h_c (T_{S.W} - T_{amb}) \quad (3)$$

where, h$_c$ is convection heat transfer coefficient W/m^2-K, $T_{S.W}$ is surface temperature and T_{amb} is ambience temperature.

2. Heat Transfer by Radiation

The heat loss is transported by the radiation (q$_r$) from surfaces of the work piece to lower temperature in the ambience can be given by (4)

$$q_r = \sigma \epsilon (T_{S.W}^4 - T_{amb}^4) \quad (4)$$

where, ϵ is the emissivity, σ is the Stefan-Boltmann constant (5.67 × 10-8 W/m^2-K^4), $T_{S.W}$ is surface temperature and T_{amb} is ambience temperature.

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III. EXPERIMENTAL SETUP

The materials which used in this study were polymer (VESTAMID® HTplus TGP3586) plates with dimensions of 1 mm thickness and 100x100 mm in width and length respectively. The Nd:YAG laser provided a laser with 1064 nm wavelength and power in the range of 1–17 W.

The most important laser processing parameters such as peak power, laser speed were used in this study with variation in specified parameters and in different combinations until identification of an optimal set of parameters. The parameters considered were the laser power (5, 10, 15, 17) W and the laser speed (20, 40, 60, 80, 100, 500) mm/sec, the total laser processes were 24 run and the time between one process and other was taking 3 sec. After the structuring process on the polymer substrate, a laser scan (Keyence Laserscan Microscope) has been used to measure the depth and the width of the removed material and to find the groove profile and the laser effect on the polymer surface.

IV. RESULT AND DISCUSSION

A. Experimental Results

From Fig. 2 which shows the laser microscope image, the effect of laser speed on the work piece surface at different speeds can be observed, where the increasing in the speed produce an decreasing in the width of the groove on the polymer surface. Also there is large effect for the laser power on the depth and width of the groove on the polymer surface at constant laser scan speed can be seen that from Figs. 3 (a)-(c), which show the 3D microscope images for the surface of the polymer.

(a) Laser speed 20 mm/sec
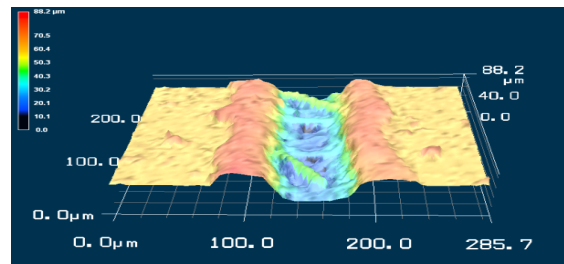

(b) Laser speed 60 mm/sec
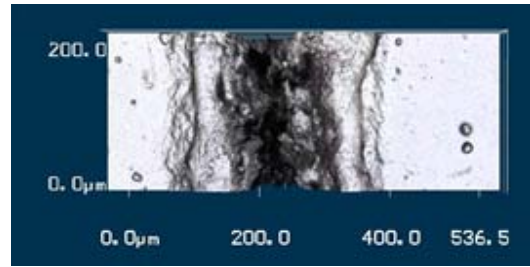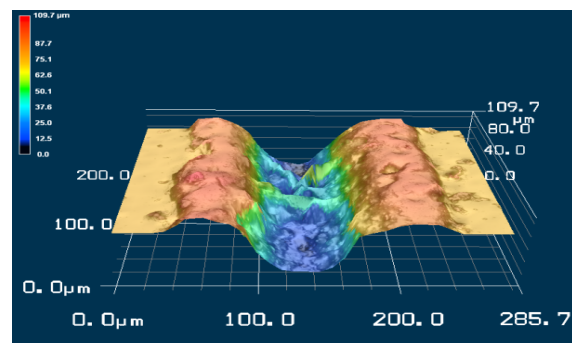

(c) Laser speed 100 mm/sec

Fig. 2 The Laser Microscope Image for the polymer surface at different laser speed and constant laser power
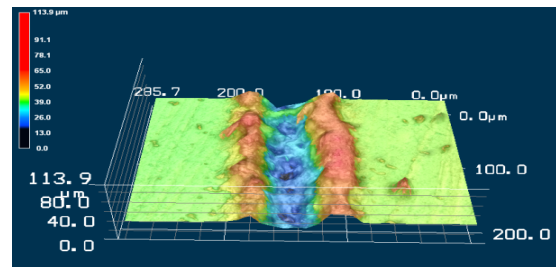
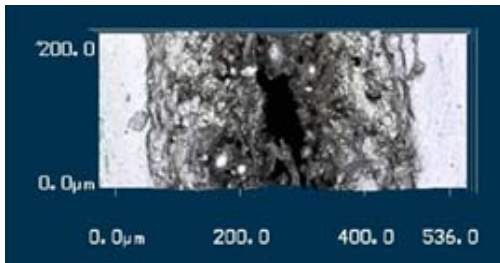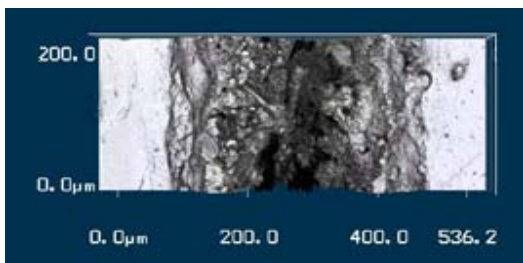(a) Laser power 5 W

(b) Laser power 10 W

(c) Laser power 17 W

Fig. 3 The Laser Microscope Image for the polymer surface at different laser power and constant laser scan speed

B. Theoretical Results

Fig. 4 shows temperature contours after 0.0195s of the heating duration and at laser speed of 300 mm/sec and at laser powers of 8 and 12 w respectively for Figs. 4 (a) and (b). The laser irradiated line is corresponds to the line along which y=0, and the maximum temperatures are always at this line during the heating and the cooling process.

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It should be noted form this figure that the temperature distribution is uniform but the value of the maximum temperature in the laser heating line increases with increase in laser power. Moreover the temperature distribution takes this form due to the small time duration of heating and cooling on the surface of the work piece and the low thermal conductivity of the polymer.
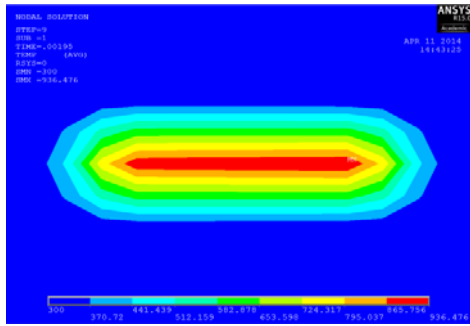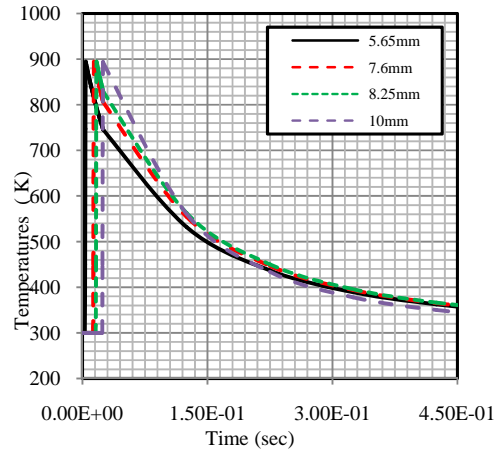

(a) The laser power 8 W
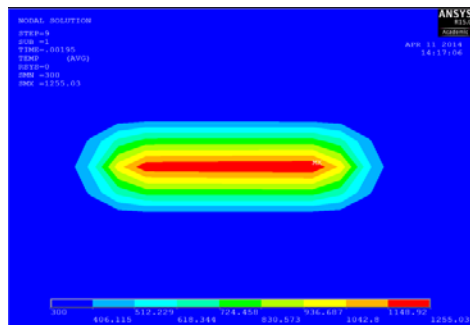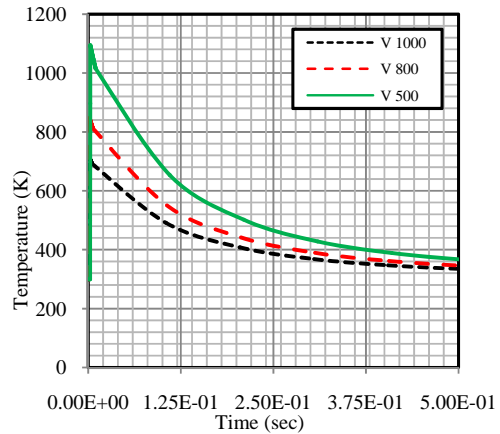

(b) The laser power 12 W

Fig. 4 The temperature contours after 0.0195 (sec) and at laser speed equal to 300 mm/sec

Fig. 5 (a), shows the variation of the temperature with time along a laser scan line at (y=0), and at different point along the laser line or x-axis (laser scanning direction) (at x= 5.65, 7.5, 8.25, and 10 mm). It can be seen from the figure that the temperature drops with time and the maximum temperatures are observed along the laser scan line Figs. 5 (b) and (c), shows the effect of the laser speed and laser power on the temperature variation with time along the laser line at point (y= 0, x =6.3 mm), it can be seen from this figure that the maximum temperature increase with decrease of the laser speed at a constant laser power or with increase the laser power at constant laser speed.

As mentioned previously, the surface of the base material during the laser process is heated then melts and consequently vaporizes due to the effect of laser irradiation. From the data of temperature distribution, we can calculate the depth and the width of the molten material and also the depth and width of the vaporized material from the surface of the polymer due to temperature increasing.

(a) At different point along the laser line (at x= 5.65, 7.5, 8.25, and 10 mm) and v 200 mm/sec

(b) The effect of the laser speed on the temperature variation at point (y= 0, x =6.3 mm) and p 17 (W)
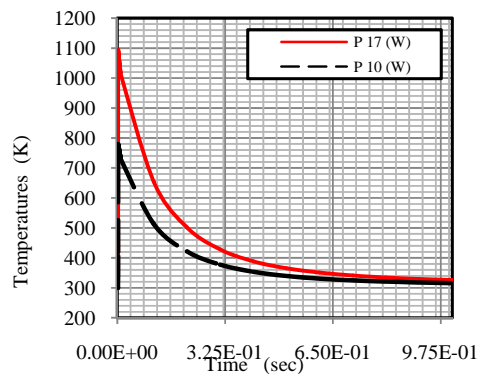
(c) The effect of the laser power on the temperature variation at point (y= 0, x= 6.3 mm)

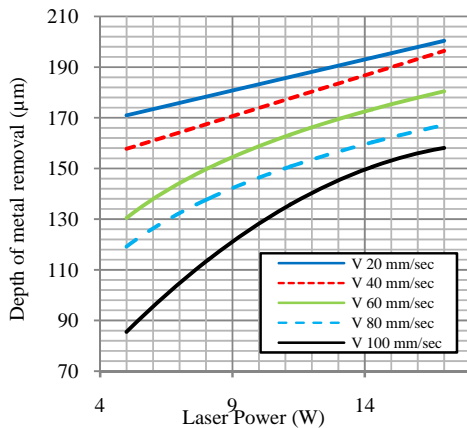Fig. 5 The temperature variation with time along the laser scan line (x-axis)

Fig. 6 shows the effect of the laser power on the depth and width of the metals surface removal at different laser speed. It can be observed from this figure that the depth and the width are increase with increase power at constant laser speed. It

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should be noted form this figures that the effect of laser power is changed with increasing the laser speed, where the effect of laser power on the depth and width is increased with decreased the laser speed, this mean in others words at high speed the effect is more than that at low speed.

Fig. 7 shows the effect of the laser scan speed on the depth and width of the metal removal. It can be observed from this figure that the relationship between the depth or width is inverse with laser speed at constant laser power, and this relation is affected by the amount of laser power which is used during the laser process, where at low power the effect of the laser speed on the depth and width of the removal metal is more than that at high power; moreover at low laser power the effect of laser speed more than the effect of laser power on the width and depth. But in general, it can be seen from Figs. 6 and 7 that the laser power and the laser speed have the same effect on the behavior of the width and depth of the removal metal.
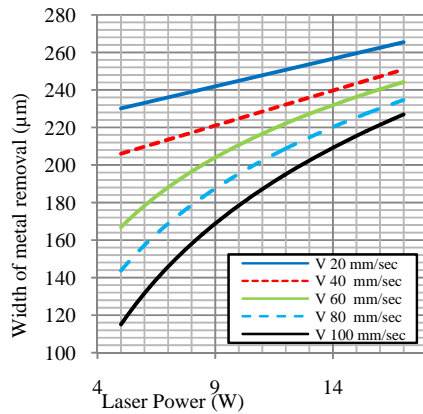
(a) The effect of the laser power on the width of the metals surface removal

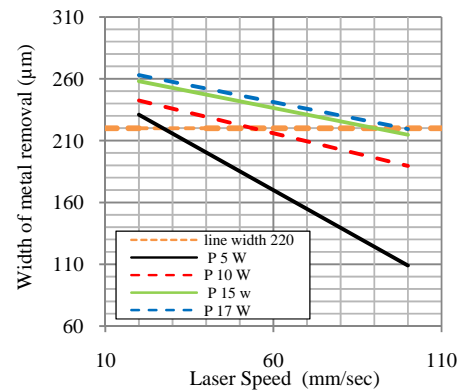(b) The effect of the laser power on the depth of the metals surface removal

Fig. 6 The effect of the laser power on the depth and width of the metals surface removal at different laser speed

These figures show that there is high flexibility in using the most important parameters like laser speed and power and it is very important to understand how these parameters can be varied in the structuring process for targeted results or for achieve high quality in this process. For example, a line with width 220 µm can be realized by four possible values of laser speed and power as shown in the table below which is concluded from Fig. 7 (a).

TABLE I
THE AMOUNT OF THE LASER POWER AND THE LASER SPEED FOR THE FOUR POINTS

Laser Parameter	1	2	3	4
Laser Power (W)	5	10	15	17
Laser speed (mm/sec)	27	54	90	98

(a) The effect of the laser speed on the width of the metals surface removal
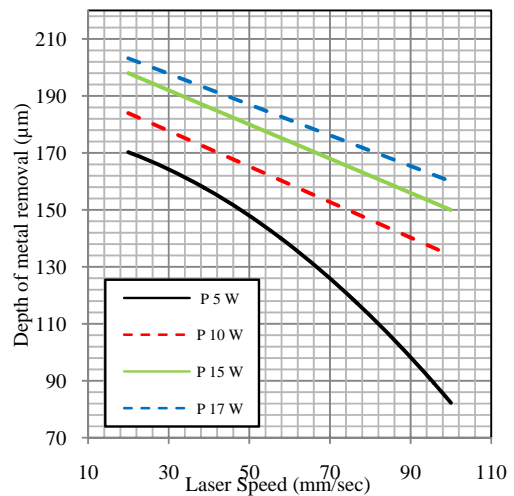
(b) The effect of the laser speed on the depth of the metals surface removal

Fig. 7 The effect of the laser speed on the depth and width of the different laser speed

It can be seen from Table I, that the four points 1, 2, 3 and 4 can been used to achieve width 220 µm, see Fig. 7 (a), but in the other hand the quality of the product is not the same for the given parameters, as mentioned previously, the increase in the laser power as well as the decrease in the laser speed led to a poor finishing quality specially along the edge of the laser structured pattern. This effect can be seen form Figs. 2 and 3

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which are show the effect of the laser speed and laser power on the quality of the laser product, where at low speed or high power the quality is decrease. This is due to the effect of the excessive heating and then the increasing in the temperature for the work piece, so that a resolidification for the edge of the laser line may occur. Therefore, prefer to use high laser speed and high or moderate laser power as possible as to achieve good quality.

In fact there are laps at the two edges of the laser line (see Fig. 8), the edge lap shape and dimensions are affected by the laser parameters. It's very important to minimize the lap dimensions (width and height) as possible as in order to achieve high quality. An experimental laser structuring tests have been made for the above four groups of the laser parameters (see Table I) in order to check up the quality and the width of the groove for the product.

Table II shows the value of the edge lap width and height for the above four laser parameters groups, also it can observed from Fig. 9, that the laser quality which is affected by the edge lap dimensions is increased when used high laser speed and high or moderate laser power.

TABLE II
THE EFFECT OF THE LASER PARAMETERS ON THE DIMENSIONS OF THE EDGE LAP FOR THE FOUR POINTS

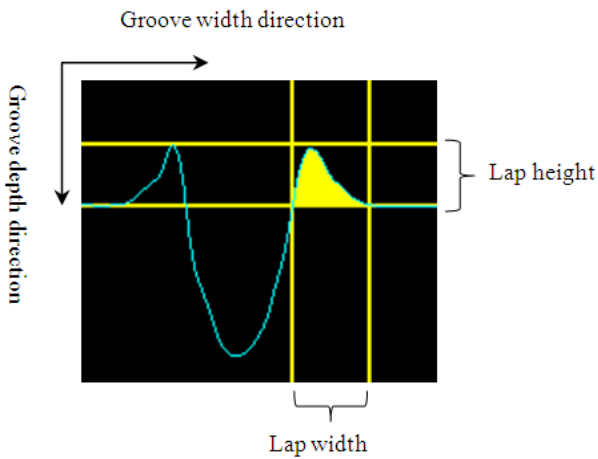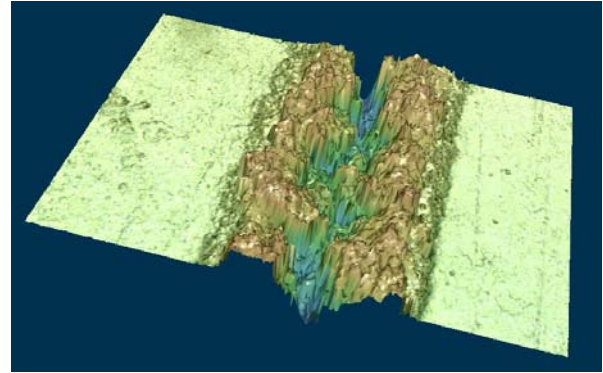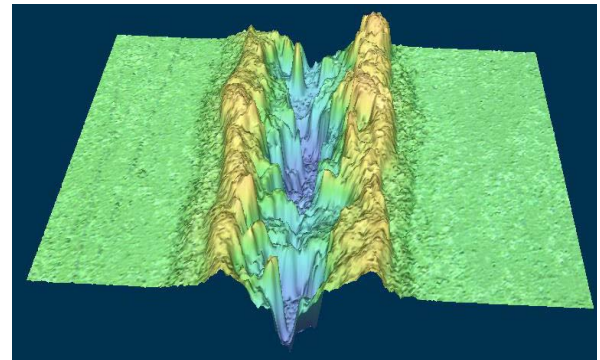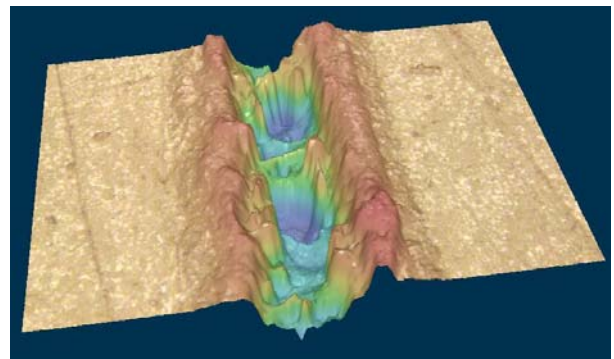| Laser Power (W)	5	10	15	17
Laser speed (mm/sec)	27	54	90	98
Experimental Width	202	211	208	210
Lap high	52	55	29	30
Lap width	110	105	87	86
The edge quality	Poor	Poor	Good	Good

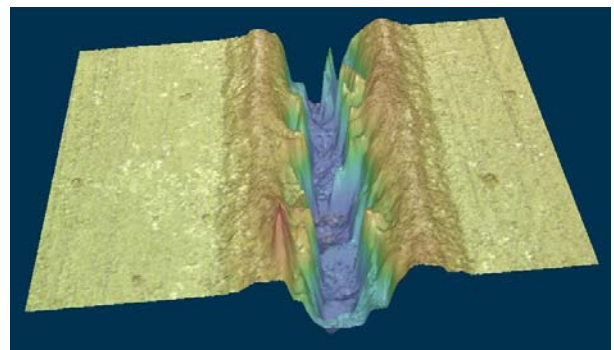Fig. 8 The groove dimensions (width and the height)

(a) 27 mm/ sec laser speed and power 5 w

(b) 54 mm/ sec laser speed and power 10 w

(c) 90 mm/ sec laser speed and power 15 w

(d) 98 mm/ sec laser speed and power 17 w

Fig. 9 The Laser Microscope Image for the polymer surface at different laser speed and laser power for the four points

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V. MODEL RESULTS COMPARISON (WIDTH AND DEPTH)

For model verification it is necessary to compare simulation results with an experimental data of different experimental laser structuring parameters. In this work an experimental procedures were carried out to study the effect of the laser power as well as laser speed on the width and depth of the removed material from the surface of the work piece. The experimental result comparison with model results shows reasonable agreement. As shown in Figs. 10 (a) and (b), it is obvious that the width and depth of removal metals increased with increasing laser power and decreased with increasing laser scan speed, this behavior is the same as for the predicted model results.
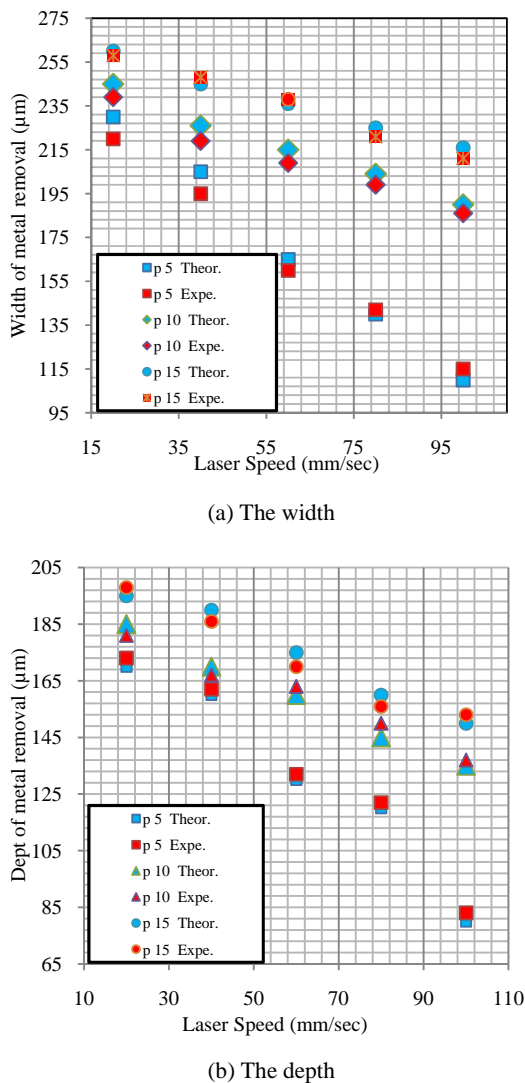

(a) The width

(b) The depth

Fig. 10 The comparison between the experimental and theoretical results at different laser power and speed

VI. CONCLUSIONS

A three-dimensional transient thermal model for the 3D MIDs (molded interconnect devices) is developed to simulate this process. This model taking in the account the effect of convection and radiations heat transfer also the laser heat source has been modeled as a moving heat source with different speed and different laser power. The following points can be concluded from this study:

1. The model results for width and depth of the removed material are comparable with the experimental results. The comparison shows a good agreement between the experimental and simulated results, which gives confidence to use the developed model with acceptable accuracy.
2. The effect of the laser scan speed is more than that for the laser power at low power, and this effect will be decrease with increase laser power.
3. The effect of laser power more than laser speed at high speed, and this effect will be decrease with decrease the laser speed.
4. For high laser quality it is suggested to use high laser speed and moderate to high laser power.

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