SIMULATION OF LASER MICRO-MACHINING

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ABSTRACT:

Our work is to improve the generation of 3D flexible structures by laser micromachining. The purpose is to extract the material by an ablation of matter in order to achieve multi-bend structure. This multi-bend part will be the key for 3D structures. For that, a frequency multiplied Nd:YAG laser equipped with a galvanometric head was used. For optimizing the laser irradiation time and power a thermal modeling of the laser matter interaction for a continuous laser impact case is presented. The paper models numerically the localized three-dimensional temperature distribution in a polyimide caused by a moving Gaussian laser beam by FEM (Finite Element Method) analysis. The beam's penetration depth, which can be described with an absorption coefficient, depends on the ambient temperature. The model examines the penetration depth and the influences of the laser motion on the transient temperature distribution. As the maximum temperature is mesh dependent we decided to chose 10 µm initial mesh with 1.01 mesh grow, so the laser beam diameter occurs 20 µm. The overall heat flux and temperature distribution on a macroscopic level are both accurate.

Keywords: 3D structure, Thermal modeling, Flexible material, Laser Source, Moving Source, Transient Heat Conduction.

1 Introduction

As the complexity of electronic systems for portable electronic, aerospace, and military applications increases, more demands are placed on lightweight and compact packaging technologies. To meet these demands, the three-dimensional (3D) packaging technology is now emerging as a breakthrough of overcoming the limit of two-dimensional (2-D) packages. With its versatility, laser processing by selective ablation of surface patterns can be used to fabricate structures into flexible polymer substrates. In this study the laser beam was used to locally heat the polyimide surface. During the simulation the laser beam moves over a surface in a line to produce the desired localized heating. The geometry under study represents the 100µm thick flexible substrate. The model examines the penetration depth and the influences of the laser motion on the transient temperature distribution. This model considers the laser beam as having an infinitesimal width and thus treats it as a line heat source.

One of the first studies was that of Tamura et al. [1]. Grigoropoulos et al. [2] solved the coupled optical-thermal problem, and the evaluation of energy absorption was obtained by a thin optic model. A similar model was employed by Chen and Tien [3] to examine the effects of temperature-dependent optical constants. Mansuripur et al. [4] studied multilayered films in two-dimensional model description. For a multi-thin film structure, irradiated by a circular Gaussian laser beam, a numerical model was proposed by Nakano et al. [5]. They considered an absorbed laser power density with an exponential decay for each layer in the thermal model. Cole and McGahan [6] extended the theory to include anisotropic thermal properties.

As the computing speed is increased by the evolution of CPUs the FEM became more popular and it gave us the opportunity to modeling and analyzing the experiments. Using this option the experiment's process parameters can be state precisely, numerically modeled and optimized so the full experiment time can be reduced.

2 3D packaging with bend-and-stay flexible

When the composite structure, which is called a flex circuit, is bent, the metal is plastically deformed and gives a mechanical strength to the structure. The objective during bending makes certain that the metal can exceed the elasticity of the polymer to hold the final shape. There are two different paths: making the copper thicker may make etching a bit more difficult; it will also take longer to etch and will use more chemistry. An alternative to reduce the thickness of the polymer along a well-defined, narrow window is preferred. This "bending window" generation is a unique application of laser material processing. A bending window can be used to define the exact position of the bending edge as well as the radius and the angle of the deformation [6].

Using the developed technology our goal is to build a 3D formation for 5 power chips from 1-sided flexible substrate. This 3D IC carrier contains the chips and it will be soldered to the PWB by reflow soldering. Our working prototype can be seen in **Fig. 1** and **Fig. 2.**

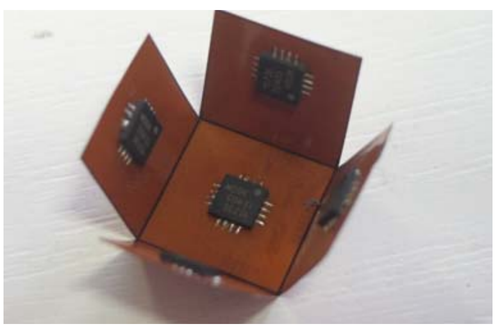


Fig. 1 Bending the polyimide at a narrow line

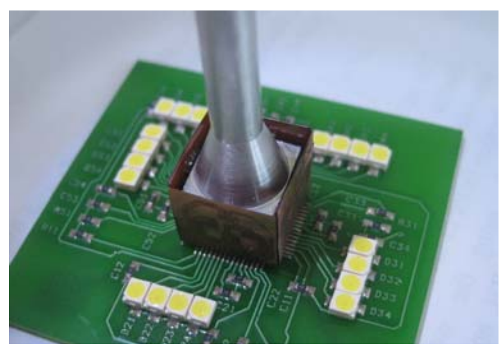


Fig. 2 Working prototype with IC cooler

3 Laser ablation of polymers

Polymers are interesting materials for many different applications due to their unique mechanical, electrical and processability properties. With its versatility laser processing by selective ablation of surface patterns can be used to fabricate structures into flexible polymer substrates. Our research is focused on the laser ablation process of polymers with UV laser [8][9].

3.1 Multilevel laser machining

Investigation on the different geometrical forms of bending windows has proved that the application of a single 'V' form window for 90° bending is not reasonable. Bends over 90° place the greatest stress on formed areas. To decrease the mechanical stress, bending with distributed parameters was used. The bending is not concentrated at one point.

In the experiments, a one-sided DuPont Pyralux flexible substrate was involved (FR9150R). The thickness of the insulation layers of the sample was 75 μm).

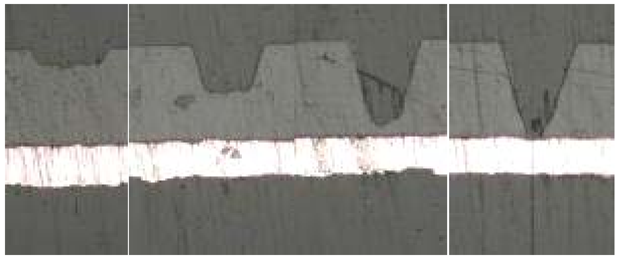


Fig. 3 Cross section of 'V' cut creation steb-by-step

The material removing process is a simple step-by-step work where the material is removed layer by layer, moving the laser beam in parallel lines. The whole 'V' shape is roughly 40 µm wide.

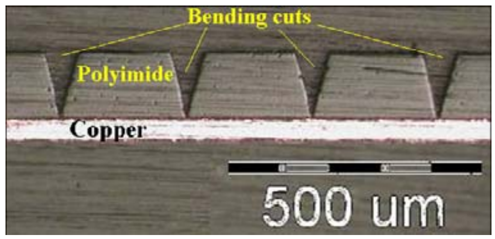


Fig. 4 Polyimide after multilevel machining

3.2 Mathematical Description

For optimizing the bending process namely the laser assisted material removing, we numerically modeled the localized three-dimensional temperature distribution in a polyimide caused by a moving Gaussian laser beam by FEM analysis (**Fig. 5**).

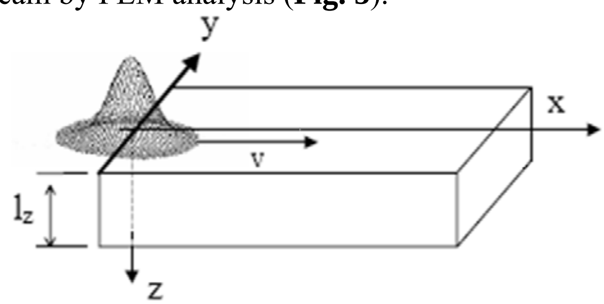


Fig. 5 A moving laser heats a thin polymer substrate.

The model simulates the substrate as a 3D object with these dimensions:
thickness: l_z=75 µm,
area: 1 x 0.7 mm^2

It handles the variation of laser intensity with penetration depth using 1D geometry that represents the substrate's thickness. The model makes use of the conduction application mode to describe the transient heat transfer in the 3D geometry. The transient energy-balance equation for heat conduction is:

$$\rho C_P \frac{\partial T}{\partial t} + \nabla(-\bar{k}\nabla T) = Q \qquad \textbf{(1)}$$

where $\boldsymbol{\rho}$ is the density, $\boldsymbol{C_p}$ is the specific heat capacity, $\bar{k}$ is the thermal conductivity, and $\boldsymbol{Q}$ is the heat source term, here set to zero (this case models the source in a different way).

The material properties are those of DuPont Pyralux flexible substrate was involved (FR9130R, 75 µm polyimide, 25 µm adhesive, 25 µm copper) [10], using an anisotropic conductivity of

(k_x, k_y, k_z) = (0.15 0.15 0.015) in units of W/(m*K), a density of 1300 kg/m^3, and a specific heat capacity of 1280 J/(kg*K) [11].

For the model, assume the boundaries are isolating. In the 1D geometry, this model uses Weak Form (partial differential equation), Subdomain application mode to model the laser penetration. In the equation describing the penetration:

$$\frac{\partial I}{\partial x} = -k_{abs} \cdot I \qquad \textbf{(2)}$$

where $\boldsymbol{I}$ represents the relative laser intensity and $\boldsymbol{k_{abs}}$ is the absorption coefficient. The absorption coefficient can depend on the temperature, and the expression used in this model is

$$k_{abs} = 8 \cdot 10^3 - 10(T - 300)\left[\frac{1}{m^3}\right] \qquad \textbf{(3)}$$

The volumetric heat source term, $\boldsymbol{Q}$, in the 3D geometry in eq.(1) is then

$$Q = P_{in} k_{abs} I \qquad \textbf{(4)}$$

where $\boldsymbol{P_{in}}$ is the total power of the incoming laser beam. Both of these equations are included and they become one equation:

$$I_{Test} \cdot (I_x - k_{abs} \cdot I) + P_{in} k_{abs} I \qquad \textbf{(5)}$$

The first part of this expression describes the penetration equation, and the second part comes from the heat-source term in the 3D Heat Transfer application mode. At the left-hand boundary the model applies a homogenous Neumann condition, and at the right-hand boundary it sets the relative intensity, $\boldsymbol{I}$, to unity. The total incoming laser power, $\boldsymbol{P_{in}}$, is 1 W.

The model implements the heat source's motion when coupling the 3D temperature variable, $\boldsymbol{T}$, to the 1-D equation. It does so with a subdomain extrusion coupling variable using a general transformation. A time-dependent transformation expression results in a moving heat source. This case describes a motion along a line:

$$x = v \cdot t, y = 0, z = x` \qquad \textbf{(6)}$$

where $\boldsymbol{x}$, $\boldsymbol{y}$, and $\boldsymbol{z}$ corresponds to the 3D coordinates, and $\boldsymbol{x'}$ represents the 1-D coordinate. Furthermore, $\boldsymbol{v}$ is the laser beam velocity, and $\boldsymbol{t}$ is time. The model sets the parameters v to 10-100 mm/s, respectively.

This method — using a separate geometry and equation to model the source term — is very useful because it provides that term directly at the test-function level. Furthermore, it models the source motion separately with the transformation expressions, making it simple to alter. It is indeed the best way to model a moving point or line source.

The 3D model makes use of an extruded triangular mesh, which has a fine resolution close to the laser incident line and is coarse elsewhere. This results in a high-resolution solution with minimum computation requirements. The mesh results can be seen in **Fig. 6**, which is set to be 10 μm in the center line.

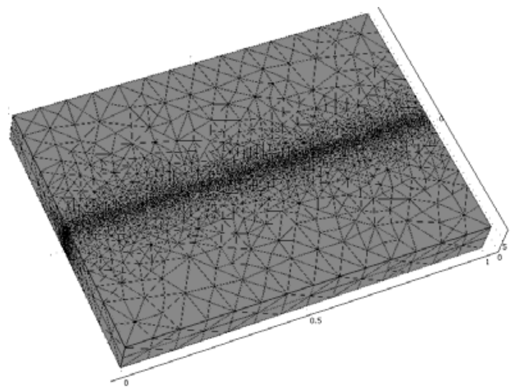


Fig. 6: The 3D mesh produced by extruding a 2D triangular mesh, refined along the laser incident line.

3.3 Numerical Model

The investigation is carried out for the polyimide film thickness 75 µm. A laser beam radius of 20 µm is chosen while the source power is set to 1W (continuous source case). Laser sources move with constant velocities v = 10 mm/s, 100 mm/s. The irradiation distribution is Gaussian and in the pulsed source case a symmetric triangular pulse is considered [12].

$$I(x) = I_{x=0} \cdot e^{-\frac{(x-m)^2}{2 \cdot \sigma^2}} \qquad (7)$$

$$4\sigma = d_{\min} = 2{,}44 \cdot \frac{fM^2\lambda}{D} \qquad (8)$$

where $\boldsymbol{m}$ is the x coordinate of the center of the beam, $\boldsymbol{\sigma}$ is the parameter of width, $\boldsymbol{d_{min}}$ is the laser diameter at focal spot, $\boldsymbol{f}$ is the focal length, $\boldsymbol{\lambda}$ is the laser wavelength and $\boldsymbol{M^2}$ is a bam quality coefficient.

Several different grid distributions have been tested to ensure that the calculated results are grid independent. The following configuration has been chosen: 10 µm initial mesh in the axial direction with 1.01 mesh grow, so the laser beam diameter occurs 20 µm. Maximum temperature differences of the fields are less than 0.1 percent by doubling the mesh nodes. The grid mesh is unstructured.

4 Results and Discussion

During the simulation the following material properties were used (Table 1.)[11].

Material Properties	Kapton
Material model	Anisotropic
Density [kg/m^3]	1300
Thickness [µm]	75
Initial Temperature [K]	300
Thermal Conductivity [W/mK]	0.120
Heat Capacity [J/gK]	1.28

Table 1. Material properties

Fig. 7 shows beam penetration into the substrate according to the equation 9. The heating at the bottom of the substrate is practically zero.

$$I(z) = I_{z=0} \cdot e^{-\alpha z} \qquad (9)$$

where $\boldsymbol{z}$ is the depth from the surface of the polymer and $\boldsymbol{\alpha}$ is the absorption coefficient.

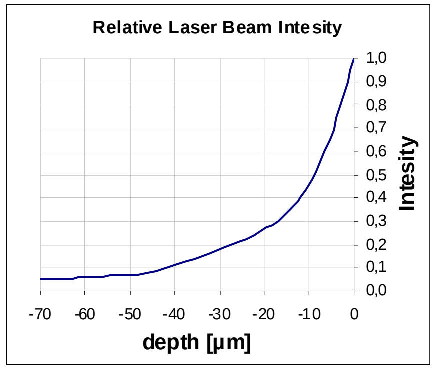
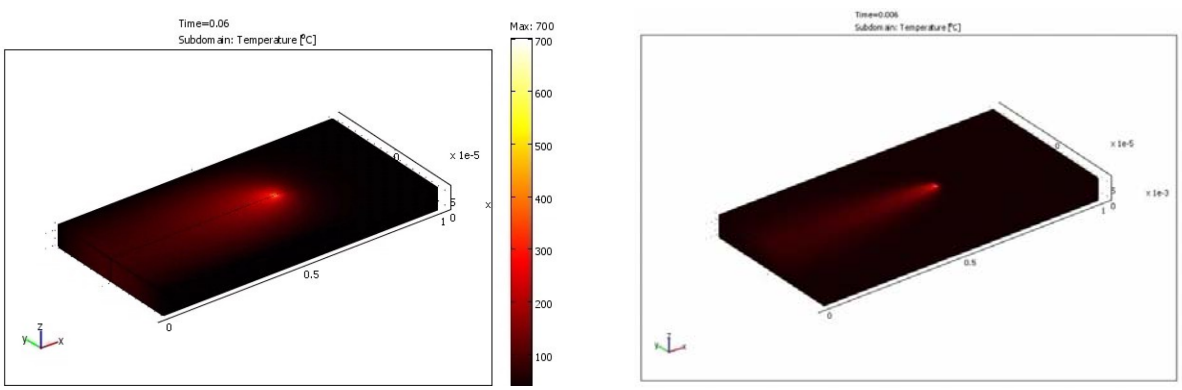


Fig. 7: Relative laser-beam intensity as a function of sample depth.

The temperature distribution at the laser-beam incident surface in **Fig. 8** depicts the:

a) lower laser beam speed v=10 mm/s with larger impact.
b) higher laser beam speed v=100 mm/s with smaller impact.

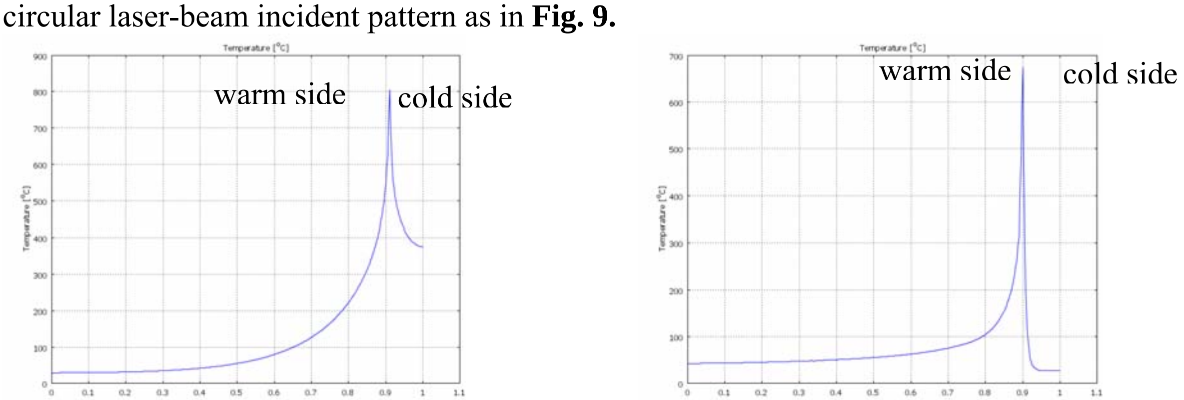


a) v=10 mm/s b) v=100 mm/s

Fig. 8: Temperature distribution after a) 60 ms b) 6 ms of laser heating (Tmin=25 °C, TMAX=700°C).

The figures clearly show a hot spot where the laser beam is located at a specific time. Furthermore, the results show a cold side and a warm side next to the vertical line below the laser beam. The warm side represents the area where the beam has just swept through.

A better way to study these effects is by plotting the temperature at the top surface along the circular laser-beam incident pattern as in **Fig. 9.**

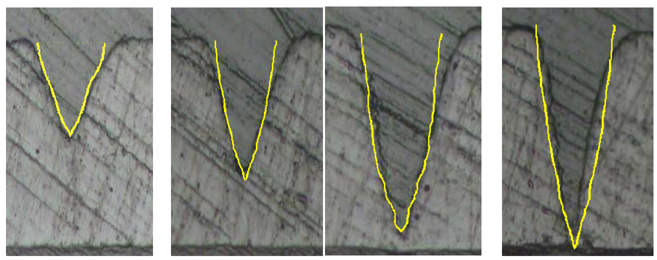


a) v=10 mm/s **b) v=100 mm/s**

Fig. 9: Temperature distribution along the laser-beam incident trajectory on the top surface after 90 and 9 ms.

Here the laser beam moves from left to right, and the warm side is on the left side of the peak. Locally the temperature reaches around 800°C, but this value is completely mesh dependent, however the mesh has been chosen close to the laser beam diameter to be accurate. If the laser beam goes at the velocity of 10 mm/s (case **a**,), the substrate at x=0 point can cool back to room temperature while at the velocity of 100 mm/s (case **b**,), the substrate at x=0 point remains 50-60 **°C,** which is over the room temperature.

Simulation resulted in surface temperature distribution and possible material ablation curves (**Fig. 10**).



a) b) c) d)

Fig. 10 Laser micro-machining and simulated profile

Verification of the surface distribution is a difficult task due to fast speed and high temperature. Even thermal imaging cameras are too slow for recording the effect. Unambiguous verification could be the cross section. The yellow curves at **Fig. 10** are simulation results, the figures are cross sectional pictures at 4 different laser powers. The experiment concluded at an almost equivalent result as the simulation, so we can state the necessity and accurate of the model.

5 Conclusions

The present numerical investigation allowed estimating the three dimensional transient thermal behavior of the heat conductive fields in semi-infinite polyimide substrate film due to a moving laser source. Temperature profiles and fields showed that the lower the laser source velocity the higher the temperature in the film and for the lowest considered velocity the thermal gradient component along the motion direction is not negligible. It is observed that the maximum temperature values reached at lowest speed; however this speed allows the substrate to cool down while new laser impulse can reach the surface. The thermal gradient along the depth are lower than the ones along the other directions.

The simulation is a possible way to estimate ablation curves is polyimide substrate.

6 References

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