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Industrial Paper

Multiphase simulation of high throughput CO2 laser via drilling for High-Density-Interconnect (HDI) applications

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Abstract

Recent advances in the compound beam positioning technology that incorporates acousto-optic deflectors (AODs) have demonstrated a superior capability in improving the process throughput and quality in industrial laser-based via drilling. In particular, an innovative intra-pulse steering approach for CO2 laser-based via drilling has been developed to drill blind-via-holes to form multi-layer interconnects in High-Density-Interconnect (HDI) substrates. However, the complex nature of process dynamics in laser-based via drilling makes it challenging for rapid process development. In this paper, multiphase simulations are carried out to explore the underlying physical mechanisms during CO2 laser via drilling in both traditional laser punch process and intra-pulse steering process enabled by AODs. The simulation results highlight the influence of the hydrodynamic motion of copper melt during the CO2 laser via drilling process and provide useful physical insights for further improvement of process quality.

Keywords: multiphase simulation and modeling, CO2 laser via drilling, AOD

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1. Introduction

In consumer electronics, semiconductor device manufacturing, and many other industries that widely employ laser micromachining technologies, there has been a growing trend towards improved processing quality and higher process throughput. The optimization of such laser processes commonly involves trial-and-error experiments. To speed up the process development, as well as to develop new process solutions, it is necessary to have an in-depth understanding of the process dynamics occurring during laser processing. While high-speed diagnostic tools enable direct observation of the process, it is still challenging to get a complete picture of the process dynamics due to the complexity of laser-induced physical processes that happen in short time- and length-scales. On the other hand, multi-physical simulation approach has been shown to provide useful physical insights into the coupled dynamics of heat transfer, melt flow and laser-induced vapor plume in laser welding, laser scribing, cutting, and laser-induced ablation dynamics, e.g. Otto et al. (2012), Otto et al. (2014), Finn et al. (2015), and Matsumoto et al. (2018).

In this paper, we utilize multiphase simulations to investigate the underlying physical mechanism involved in CO2 laser via drilling in HDI applications. Specifically, these simulations are designed to examine the top copper opening process in a multi-layer Cu-FR4-Cu stack commonly found in print-circuit-board (PCBs) structures. Furthermore, a novel intra-pulse steering approach enabled by AOD technologies is explored through the simulations, and the results are compared with the experiments at the same laser process conditions.

2. Simulation Details

The simulations presented in this paper are carried out using a multiphase simulation package developed through a collaboration between the Vienna University of Technology (TU-Wien) and mks|ESI. The simulation solver is designed to model industrial laser processes involved in many applications e.g. laser cutting, drilling, and scribing. Briefly, the simulation model considers the laser beam propagation to the work surface, the interaction

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of the laser beam with the target, including absorption, reflection, and transmission. The coupled heat transfer and Navier-Stokes equations are solved to account for the convective and conductive heat transfer during laser processing, as well as the fluid or gas flow when the target material is melted or vaporized. Furthermore, the model takes into account the recoil pressure from the vapor that leads to the deformation of the free surface as it expands into the surrounding medium. The free surface of the material is computed through a volume of fluid (VOF) approach. Further details of the simulation model can be found in e.g. Otto (2012) and Otto et al. (2014).

For the laser-based via drilling process in HDI applications, a CO2 laser pulse is commonly used to drill through the top copper layer and middle FR4 material to expose the inner copper pad to form a blind-via-hole (BVH) as shown in Figure 1(a). The top copper layer considered in this study has a thickness of 12 μm and is typically oxidized to enhance the laser absorption of the CO2 laser beam (Hirogaki et al. 2009). The absorption of the copper layer is calibrated through existing process data and an average absorptivity of 27% is chosen for the top copper layer in all the simulations in this study. Note that the wavelength of the CO2 laser used in the simulations and the experiments is 9.4 μm. To simplify the simulation geometry and speed up the multiphase simulation, the middle FR4 layer consisting of glass-fiber bundles and epoxy resin is represented by a homogeneous layer of epoxy resin with a thickness of 50 μm in the simulations. The typical material properties needed for the multiphase simulation such as optical, thermal and transport properties of copper and epoxy resin can be found in Bäuerle (2011).

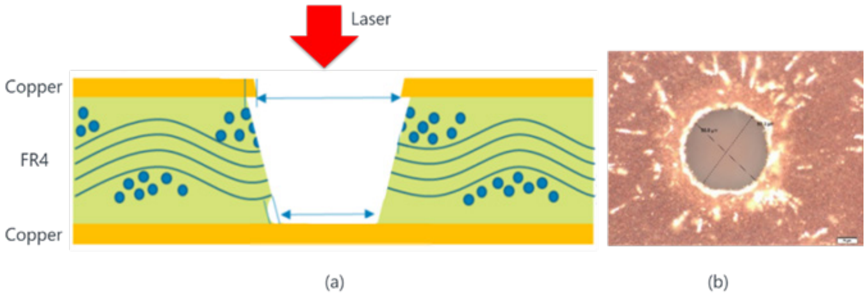


Fig.1. (a) Schematic view of the cross-section of a blind via (b) Top view of a blind via drilled by a CO2 laser pulse described in Section 3.1

3. HDI Via Drilling Simulations

3.1. Laser Punch Process

The commonly used laser punch process for CO2 laser via drilling is to directly irradiate the CO2 laser beam at the same location of the sample for the full duration of the pulse. During the laser irradiation, both the top copper and resin layers are removed to form a via hole. This process is also called Cu direct drilling (Okada et al. 2012). Figure 1(b) shows a top view of a blind via created by such a process using a CO2 laser pulse with a total pulse energy of 7.2 mJ and a pulse duration of 13 μs. The resulting top opening size in the copper layer is measured to be ~79 μm.

To understand how the copper opening occurs during the via drilling process, a multiphase simulation was carried out for a 12μm copper residing on a 50μm epoxy resin. The laser intensity distribution for the CO2 pulse was simulated using a top-hat spatial profile with an effective spot size of 120 μm and a 13 μs rectangular shape for the temporal profile. Figure 2 shows the sequence of the copper opening process at four different times. It can be seen that at the time of ~5 μs, the absorption of the laser energy increases the temperature at the copper surface above the melting point (T_m=1358K for copper), as identified by the melt zone boundary in the temperature distribution (Fig. 2(a)) and the liquid copper shown by the red-colored region (Fig. 2(b)). Due to the fast thermal conduction in the copper, the heating of the top copper layer by the CO2 laser also leads to a temperature rise beyond the glass transition temperature (or melting temperature of 433K used in the simulation) of the epoxy resin near the interface of top copper and epoxy. As more laser energy is absorbed on the copper layer, the heating of the copper surface creates a temperature gradient across the layer, driving the propagation of copper melting front toward the Cu/epoxy interface. Before the melting front reaches the interface, the temperature near the interface already exceeds the typical decomposition temperature of epoxy (a nominal value of 1000K for the boiling point is used in the simulation). In other words, the epoxy resin near the interface has decomposed and created a strong vapor pressure underneath the copper layer. As soon as the copper melting front reaches the interface, large vapor pressure from the resin underneath liquid copper drives the explosive ejection of the copper melt between 7 and 9 μs. Consequently, once the top copper layer is removed, the laser energy in the remaining CO2 pulse is absorbed primarily in the resin until the bottom copper layer is exposed (not modeled in this simulation).

Furthermore, the multiphase simulation also suggests that apart from the difference in the copper melting point and the epoxy decomposition point, fast heat conduction in copper could play an important role in the generation of the overhang of the via, which is typically measured by the size of the resin being removed below the top copper (Fig.1). The simulation shows that even before the ejection of the copper melt occurs, the heating near the copper/epoxy interface extends beyond the region of the final copper opening, creating a liquid resin phase underneath the copper layer (green in Fig. 2(b)). This observation suggests that the optimization of peak power and the pulse duration of the CO2 laser pulse would be necessary to reduce the overheating of the top copper layer to avoid large overhang in the laser-drilled via and to achieve a good via quality that is required for copper plating.

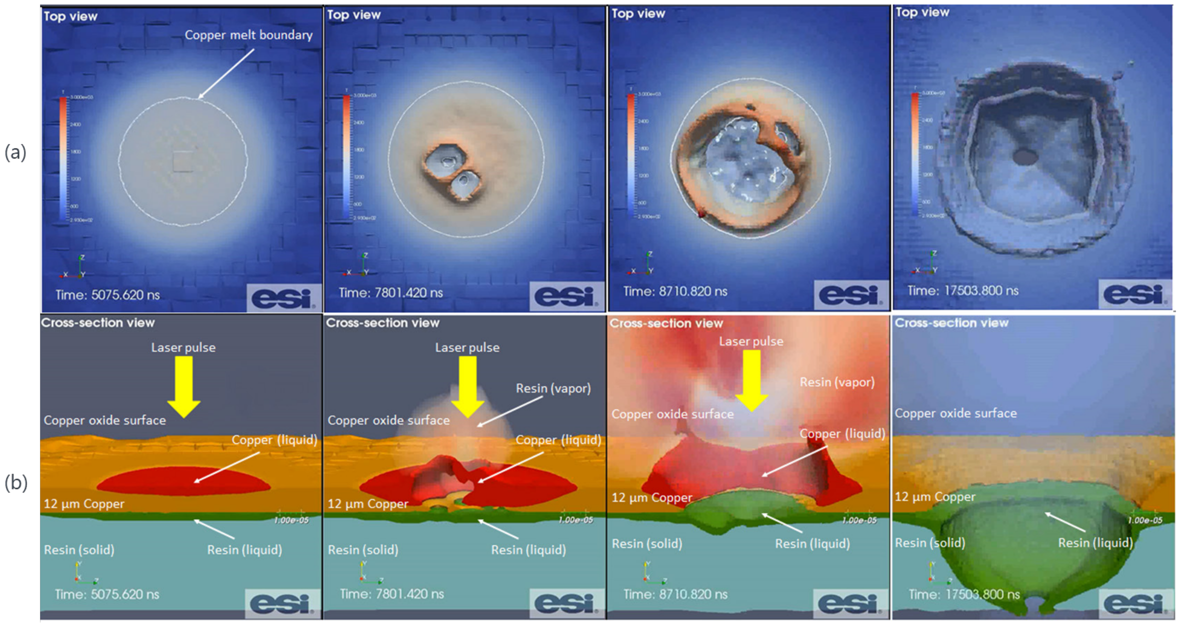
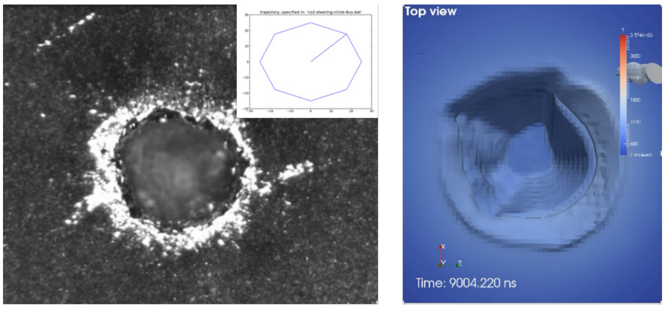


Fig. 2. (a) Top view of the temperature distribution; (b) Cross-section view of different phases in the simulations during the copper opening process by a CO2 laser punch process. White lines in panel (a) shows the position where the copper melting temperature is reached.

3.2. Intra-pulse Steering Process

Recently, a novel compound beam positioning technology by combining X- and Y-axis translation stage and galvanometer-driven mirrors, along with AODs was developed to achieve higher laser processing throughput. Detailed information regarding this approach can be found in U.S. Pat. No. 6,706,999. Specifically, this approach enables spatially steering a CO2 laser pulse on the work surface during the pulse (Geode Acceledrill^{TM}). The idea of intra-pulse steering is to move the CO2 laser beam along a pre-defined trajectory on the work surface to create a wide range of via sizes that are not readily accessible by a traditional laser punch process using a single laser spot size, thus offering both process flexibility and throughput advantages. On the other hand, in contrast to the traditional laser punch process, intra-pulse steering effectively distributes the laser pulse energy on a large surface. As discussed in Section 3.1, the fast heat conduction in copper can lead to the rapid dissipation of the absorbed energy in both lateral and vertical directions across the copper layer. Therefore, it remains unclear whether the intra-pulse steering approach is feasible to create a copper opening to form a via.

To answer this question, a multiphase simulation was carried out to explore the copper removal when a CO2 laser beam is moving along a trajectory shown in the inset of Fig. 3(a). The total pulse energy is 5 mJ for an 8 µs CO2 laser pulse with a 1/e^2 spot size of 70 µm. As seen in Fig. 3, the overall shape of the via is similar between the simulation and the experiment. In particular, the averaged top copper opening predicted from the simulation is ~95 µm, within the range of top opening, 91-106 µm, from the experiment in a multi-layer Cu-FR4-Cu stack.



(a) (b)

Fig. 3. Top view of a via hole drilled by the intra-pulse steering process of a CO2 laser pulse: (a) experiment; (b) multiphase simulation. The inset in (a) shows the CO2 laser beam trajectory used in both the experiment and the simulation.

To further improve the via roundness, σ, to meet the via quality requirement, typically σ≥90%, it is necessary to understand the influence of CO2 laser beam movement on the via roundness. Figure 4 shows an example of the modification in the via shape due to a change in the effective laser scan speed during the intra-pulse steering process. For a 10 µs CO2 laser pulse @ 500 W steering along a circular trajectory on the work surface, a significant difference in the via shape was observed between two laser scan speeds: 20 m/s and 120 m/s. As shown in the multiphase simulations, in the case of a slower beam movement at 20 m/s, the copper opening occurs at ~4.5 µs and the subsequent via drilling process proceeds with the hydrodynamic movement of copper melt zone, which is driven by the recoil vapor pressure of epoxy resin created during the remaining part of the pulse. When a faster scan speed of 120 m/s is used in the process, the copper opening is delayed to ~6 µs as the incident laser energy is spatially distributed on a larger surface area. Consequently, a wider copper melt zone, as identified by the melting temperature in Figure 4 (b), is observed before the copper opening happens. It is shown that the copper opening initiates near the center of the melt zone where the laser heating is maximized, and the final via shape after the removal of the melted copper is significantly rounder than the one created at a lower laser scan speed.

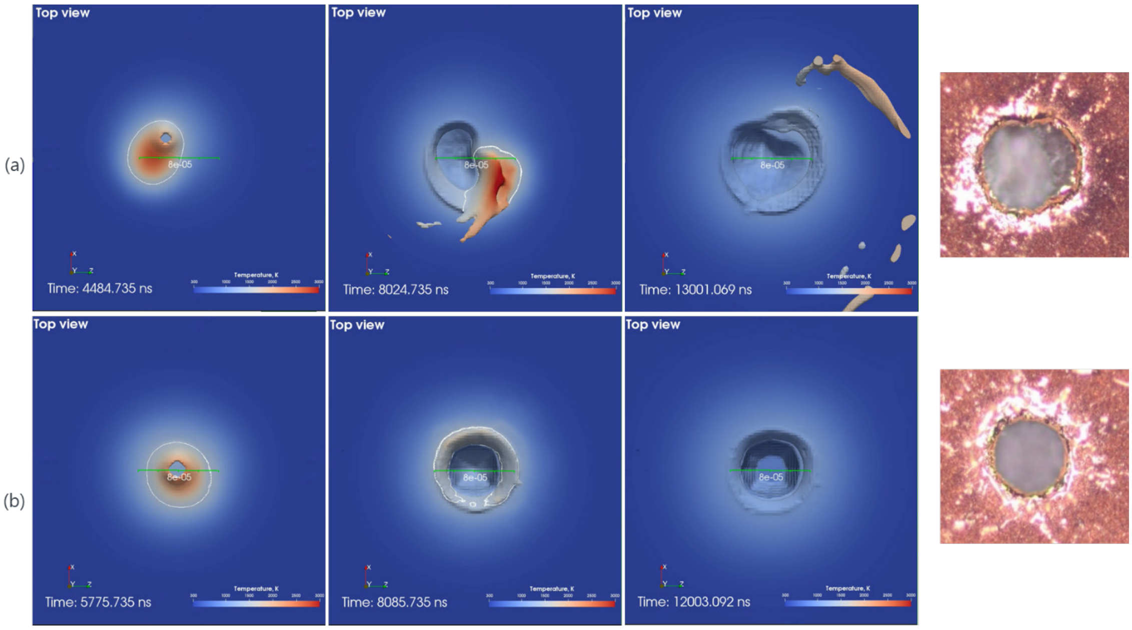


Fig. 4. Top view of the temperature distribution of a via drilled by intra-pulse steering of a CO2 laser pulse from multiphase simulations at (a) effective laser scan speed of 20 m/s; (b) effective laser scan speed of 120 m/s by a 10 µs CO2 laser pulse @500 W using a circular trajectory. The corresponding experimental images of the via drilling are shown on the right. The white lines on the temperature distribution show the copper melt zone boundary.

4. Summary

Multiphase simulations are carried out to explore the process dynamics in the copper opening process for CO2 laser via drilling in HDI applications. Examples are shown for both the traditional laser punch process and the intra-pulse steering process enabled by advanced AOD technologies. It is found that large vapor pressure of the epoxy resin near the interface between top copper and resin is the driving force for an explosive ejection of the copper melt zone in connection to the formation of the via hole. The hydrodynamic motion of the copper melt is shown to be responsible for the change in the via shape, when different laser scan speeds are applied during the intra-pulse steering process, suggesting that advanced beam control through AOD technologies has a great potential to improve the process quality and throughput.

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