

Monitoring of Excimer Laser Ablation of Multi-layer Thin Films by Acoustic Emission

by

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Abstract

In micromachining, excimer laser ablation was a key process for producing featured by removing parts of a photoresist layer. One hurdle was that the seed layer (e.g., copper), on which the photoresist was spun, was easily attacked or damaged in laser ablation of the photoresist. To overcome this drawback, an acoustic emission transducer (AET) was coupled to the X-Y stage of an excimer laser system to acquire surface acoustic waves (SAWs) arising from pulsed laser-material interaction. The characteristics of such a process could then be investigated by analysing this feedback signal. The sequences of acoustic emission signals were transformed to frequency domain by employing fast Fourier transformations (FFTs). Analysis of the frequency spectrum showed that there were few dominant frequencies correlating with the ablation process through one material to another. Specifically, the amplitude of the dominant frequency was a function of the number of pulses, where an abrupt change could be found when laser beam approached the interface of two layers. The exact number of shots machining through one material was indicated by properly calibrating the function at given laser parameters. In turn, the etch rate of machined material could be calculated by averaging the thickness of this material with number of shots. Thus, a real-time monitoring scheme of complex laser micromachining process could be realised on the basis of taking SAWs as feedback signals.

1. Introduction

Manufacturing industries had used laser micromachining in many high-tech application areas in which microfabrication was an enabling technology. Laser micromachining had become a very popular tool for fabricating three-dimensional (3D) structures in various materials including ceramics, glasses and polymers. In particular, excimer laser ablation of polymers had found many practical applications. When fabricating multi-level 3D structures, attacking or deteriorating the plating base was one of the hurdles because there was no on-line calibration tool to fix this problem and optimise laser parameters in process (Ghantasala; Hayes; Harvey, and Sood 2001; Jin; Harvey; Hayes; Ghantasala; Dowling; Solomon, and Davies 2001). Facilities such as an

optical microscope and scanning scope were frequently employed to calibrate the process.

Alternatively, acoustic wave detection had proven a promising tool to evaluate laser ablation process. Acoustic emissions were stress waves that travelled through a material as a result of some sudden release of strain energy. During high-power, short-pulsed laser-material interactions, very high stresses resulted from thermal expansion and phase change, as well as recoil momentum and shock waves which were induced by high velocities of the ablation products. At low laser energy flux, below the vaporization threshold, the generation of photo-acoustic waves was caused by the photo-elastic effect of the laser pulses on the target. At higher laser energy flux, when a laser pulse with a power density greater than ablation threshold irradiated a solid target, the target material would successively melt, evaporate, and become plasma. The plasma sharply exploded at an initial speed of up to 10^5 m/s into the ambient air with high pressure that induced a shock wave (Dogas; Efthimiopoulos, and Andreouli 2001; Petzoldt; Reig, and Matthias 1996; Petzoldt and others 1996; Zweig; Venugopalan, and Deutsh 1993; Chen; Ni, and Lu 2000). Moreover, with laser induced stress release in target samples, longitudinal and shear waves were transmitted in the body of the target and surface acoustic waves (SAWs) propagated along the surface of the target.

The correlation of acoustic emission with the laser cleaning process was derived by detecting audible acoustic waves of laser-material interaction through a microphone (Lu; Hong, and Chua 1996; Zhu; Lu; Hong, and Chen 2001). On the basis of appropriately calibrating the correlation, a real-time monitoring and control strategy for laser cleaning process was achieved with the implementation of software and hardware (Lu; Meng, and Hong 1998). Such work was improved by introducing an artificial intelligence algorithm. Lee *et al.* developed a real-time fuzzy expert system to predict substrate damage in laser cleaning process (Lee; Watkins, and Steen 2000).

A variety of AE transducers were applied to investigation of laser-material interaction through detecting laser induced SAW, longitudinal and shear wave in target. Because AE transducers were very sensitive and had wide bandwidths, AE events detected by them were rich in information (Shannon; Rubinsky, and Russo 1996; Lee and Dornfeld 2001). The results showed a clear correlation between physical process parameters and the AE signals.

In this paper, an AE sensor is used to detect acoustic signals of laser micromachining multi-layer thin films. The correlation of AE with laser micromachining process is established through analyses. A real-time monitoring strategy is presented herein.

2. Experiment

The sample for the experiment was a multi-layer film: a layer of laminar AX dry film photoresist at a thickness of ~ 35 μm (Dynachem Inc., USA) together with a layer of polystyrene at a thickness of ~ 25 μm were laminated onto a PCB clad with copper (the thickness of ~ 30 μm .) as shown in Figure 1.

Lamination was performed by using a Dynachem laminator. The sample was ablated using an excimer laser system.

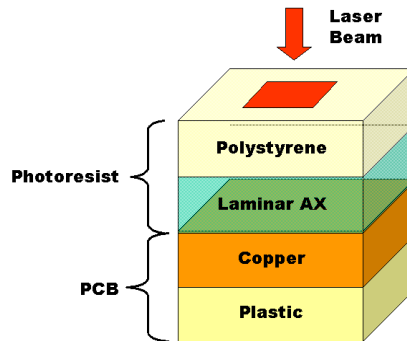


Figure1 - The illustration of the multi-layer thin film sample

Figure 2 shows the experimental arrangement for detecting AE signal of excimer laser micromachining process. A KrF laser system Series 8000 (Exitech Limited, UK) was used as the laser beam source. The laser beam had a wavelength of 248 nm and a pulse duration of around 20ns. The beam after passing through the homogenizer was focused by a quartz lens. The sample to be processed was placed in air with its surface perpendicular to the incident laser beam. A piezoelectric acoustic emission transducer (AET), with a bandwidth of 100kHz to 1MHz, was fixed upon x-y stage of the excimer laser system to detect the surface acoustic wave (SAW) arising from laser-sample interaction. The AE signal was amplified by a pre-amplifier with 60 dB gain and sent into a digital oscilloscope (TDS3000) as signal. The synchronous output of the laser controller was used as a trigger signal for signal acquisition of oscilloscope. The acoustic waveform was displayed, digitized and saved to a soft format by the oscilloscope, and then sent to a PC for the purpose of data storage and further processing.

3. Results and Discussion

The acoustic waves generated by laser irradiating the sample were recorded and analysed using the precedent arrangement.

Figures 3(a) to 3(d) show the time series of the acoustic waveforms and their frequency spectra by employing FFT when ablating the sample at shot numbers 10, 100, 200 and 1000 respectively. The fluence of the excimer laser was set to $\sim 0.63\text{J}/\text{cm}^2$ and the irradiated area 1.4 by 1.4 mm. During the course of the process, polystyrene and laminar AX were ablated through, in turn. Shot 10 was the through shot in the course of ablating polystyrene and shot 100 in the course of ablating laminar AX. Shot 200 and 1000 were associated with laser interaction with the copper surface rather than laser

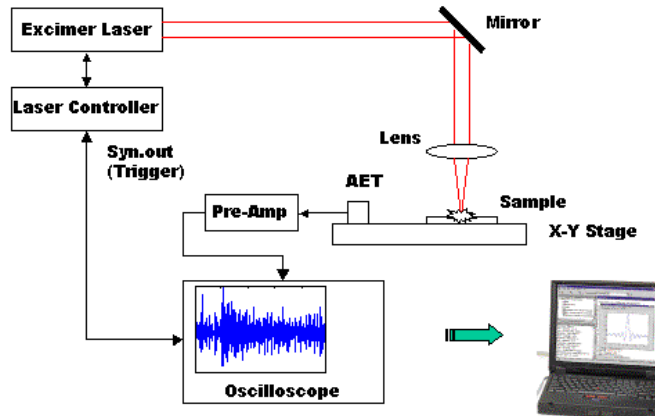


Figure 2 - Experimental Set-Up for Acoustic Wave Detection of Laser Micromachining

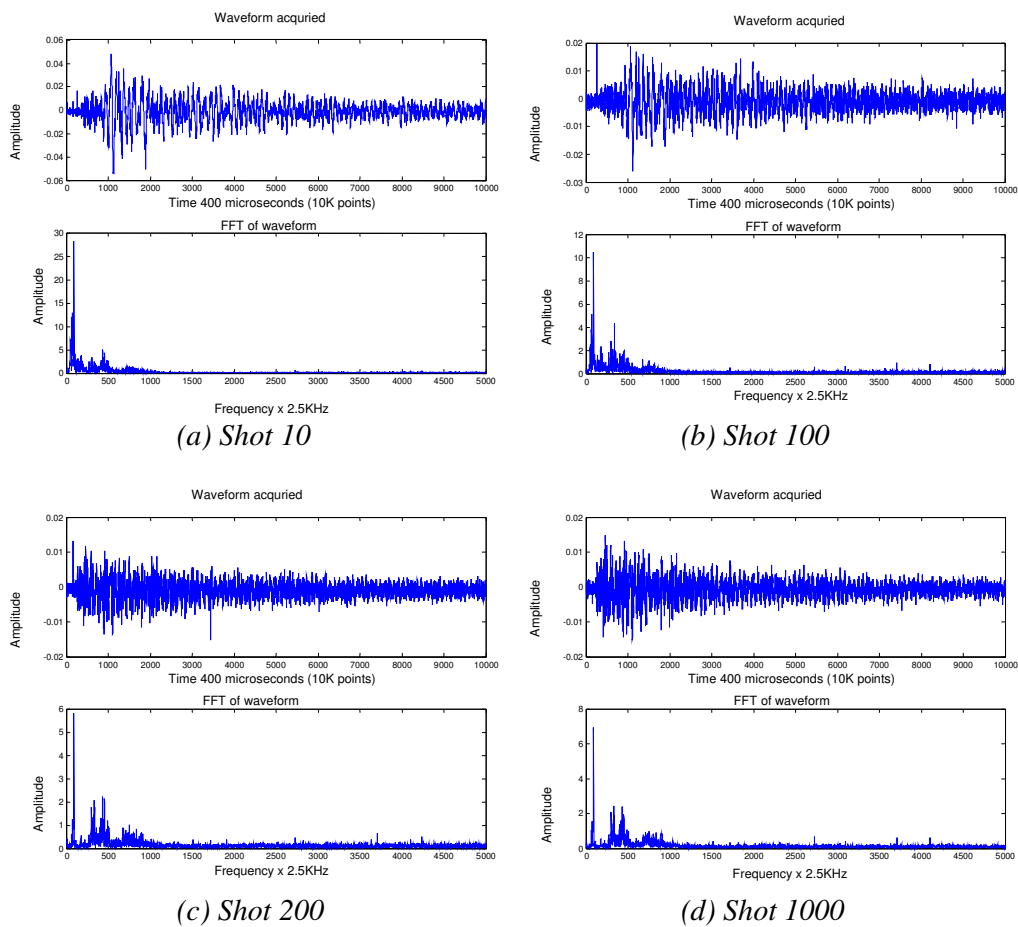


Figure 3 - The Time Domain Waveform and its Frequency Spectrum at Shots 10, 100, 200 and 1000 Respectively

ablation of copper because the laser fluence was lower than the ablation threshold of bulk copper ($\sim 1.88 \text{ J/cm}^2$). It could be seen from these figures that the acoustic waveform indicators could be identified at shot 10 and shot 100 – these being an exponentially decaying waveform. Their counterparts at shot 200 and shot 1000 were more obscure because faint AE signals were shielded by noise arising from the physical arrangement. In comparison, the frequency spectra in all cases were much clearer in the range of 100kHz to 1MHz, the bandwidth of sensor. Moreover, there was a dominant frequency at about 230 kHz (this frequency value dependent on x-y stage, sample properties etc.).

Figure 4 shows the plot of the peak amplitude value of the dominant frequency in the frequency spectrum versus the number of employed shots. In this graph, there were three fluctuating flat stages explicitly divided by two sharp drops. From inspection during laser micromachining, the final removal of the remainder of the polystyrene in the exposed area occurred at around shot 70 and the final removal of the remainder laminar AX in the exposed area at around shot 157. These were consistent with two drops in the graph. Therefore, this graph described the laser ablation process of the multi-layer thin film from phase to phase. The three fluctuating stages represented laser interaction with polystyrene; laminar AX, and copper respectively. Two drops denoted not only where the ablation process transferred from ablating one material to another but also how fast this transition was through the evaluation of the slope curves.

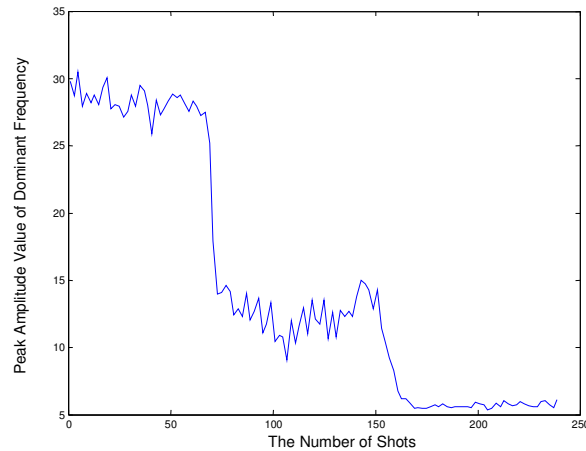


Figure 4 - The Peak Amplitude Value of Dominant Frequency in Frequency Spectrum Versus the Number of Shots when Micromachining Sample (ii)

As a result, there were quite a few potential applications which could be inferred from the correlation of AE events with laser micromachining.

From Figure 4, the etch rates of polystyrene and laminar AX at fluence $\sim 0.63 \text{ J/cm}^2$ were deduced by averaging their thickness with employed shots— approximate $0.347 \text{ }\mu\text{m}/\text{shot}$ and $0.438 \text{ }\mu\text{m}/\text{shot}$ respectively. Therefore, detecting AEs

provided a new means to calculate the etch rate. In comparison, the existing method of the determining the etch rate of a material at given laser parameters was mainly an ablation rate measurement which was heavily dependent on other measurement devices such as optical microscope.

It should be noted, however, that the property of a photoresist in different samples was not always consistent and laser beam properties varied from time to time. Both of these factors affected the calculated etch rate of samples.

Another potential advantage of the real-time monitoring process that could be achieved through the application of AE was that the laser micromachining process could be optimised in real time, based on the correlation of acoustic waves with the ablation of materials. In many applications, it was desirable to achieve sharp wall angle in photoresist. It was well known that the higher the fluence that was employed, the sharper wall angle gained. As an assumption, the initial laser energy was set at higher fluence in order to achieve the sharp wall angle in material. When laser beam approached the underneath substrate, the fluence was adjusted to lower value to avoid damage to the substrate. As shown in Figure 4, one of significant drops in the dominant frequency curve acted as an indicator of finalising the ablation of a layer of material.

Thus, the correlation of AE signatures with the process could be applied to optimise the process on-line with execution of a real time monitoring and diagnostic system in a computer. However, in order to construct such a correlation over a range of materials, the mechanism of laser-material interaction need to be understood in depth through investigation of experimental results and exploration of theory model.

4. Real Time Monitoring Strategy

The initial experimental arrangement introduced in Section 2 was straightforward to configure in order to determine the AE signal of interest. However, it was only suitable for detection of one waveform at a time due to rudimentary device constraints. Figure 5 illustrates the more practical arrangement for real-time monitoring of the laser micromachining process that will be utilised in ongoing research. Instead of an oscilloscope, a data acquisition board and personal computer were used to acquire a sequence of AE events, each of which was triggered by a synchronous output signal of laser controller. A monitoring and diagnostic system was run on the same computer. Features related to the process could be extracted by performing signal processing functions. By executing an artificial intelligence algorithm for these features, a diagnostic result for the process could be determined. Finally, according to the results, the system could provide an on-line report for a machine operator or send a feedback control signal to an excimer laser controller to optimise the process.

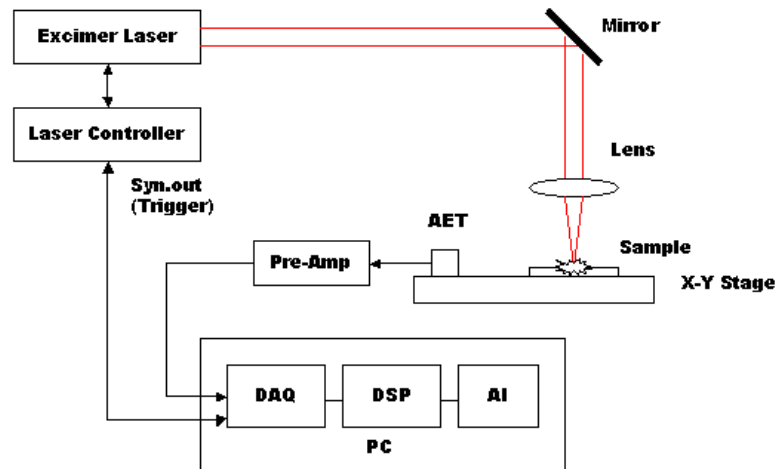


Figure 5 Schematic Diagram of the Experimental System for Real-Time Monitoring and Diagnosing of Excimer Laser Micromachining

5. Conclusion

Acoustic emissions, arising from excimer laser micromachining of a multi-layer thin film, were investigated through coupling an acoustic emission sensor on x-y stage of excimer laser system. It was found that the peak amplitude value of the dominant frequency of an acoustic wave had a significant change as the laser ablated through one layer to another. Accordingly, correlations of acoustic emissions with excimer laser micromachining could be constructed. With proper evaluation of the transitions in the process, the etch rate of a material at the given laser parameters could be calculated. Finally, a real-time monitoring and diagnosis strategy for laser micromachining could be addressed. This strategy therefore had the potential to provide a real time calibration tool to optimise the process. However, the mechanism of laser-material interaction was still implicit at the time of implementation of this paper. It required further investigation in terms of scientific and technical perspective.

6. References

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