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A study of substrate temperature distribution during ultrashort laser ablation of bulk copper

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Abstract

With the aid of an infrared thermograph technique, we directly observed the temperature variation across a bulk copper specimen as it was being ablated by multiple femtosecond laser pulses. Combining the experimental results with simulations, we quantified the deposited thermal power into the copper specimen during the femtosecond laser ablation process. A substantial amount of thermal power (more than 50%) was deposited in the copper specimen, implying that thermal effect can be significant in femtosecond laser materials processing in spite of its ultrashort pulse duration.

Keywords: Ablation; Copper; Femtosecond laser; Thermal effect

1. INTRODUCTION

The technique of laser ablation with laser pulses ranging from microseconds down to very short pulses in the femtosecond (fs) regime has a wide range of applications (Fernandez *et al*., 2005; Jungwirth, 2005; Thareja & Sharma, 2006; Gamaly *et al*., 2005). In this paper, we demonstrate that ultrashort or fs laser ablation is a useful technique for processing of different materials with high precision (Preuss *et al*., 1995; Chichkov *et al*., 1996; Liu *et al*., 1997; Nolte *et al*., 1997). Compared to long-pulsed (nanosecond or longer) laser pulses, the ablation of materials by fs laser pulses reduces the thermal and mechanical effects on the surrounding materials, and therefore improves the quality of the processed features (e.g., holes, cutting kerfs, and grooves). Although the thermal and mechanical effects are reduced in fs laser ablation, recent studies showed that these effects are still present and even significant. Most of the studies focused on the observation of the heat affected zone (HAZ) surrounding the area ablated by fs laser pulses by using off-line techniques such as scanning electron microscopy (SEM) (Borowiec *et al*., 2003), transmission electron microscopy (TEM) (Le Harzic *et al*., 2002), and X-Ray diffraction (XRD) technique (Hirayama & Obara, 2002). Recently, the calorimetric technique has been employed to measure the residual thermal energy deposited into the bulk of materials. These investigations indicate that thermal effect is indeed important in fs laser ablation. In our previous study on silicon specimens (Tran *et al*., 2006), using an infrared thermograph technique, we reported direct observation of the *in situ* temperature field of a crystalline silicon specimen ablated by multiple fs laser pulses. In addition, the amount of deposited thermal power was estimated to be more than two-thirds of the incident laser power. Our study further provides evidence that thermal effect is indeed significant in fs laser processing.

In this study, we extend our investigation to the thermal effect during fs laser ablation on copper, which is a metal of good conductivity. Due to its high thermal and electrical conductivities, copper is an important material and has a variety of applications, especially in integrated circuit fabrication. Fs laser ablation of copper is an important manufacturing process for drilling micro-holes and cutting small tracks. A recent study on fs laser ablation of copper showed that thermal effect cannot be neglected in fs laser ablation (Hirayama & Obara, 2005). However, this study employed an off-line technique by observing the HAZ after ablation with fs laser pulses. Using the infrared thermograph technique, we directly observed the *in situ* temperature field during fs laser ablation of copper. Combined with simulation studies, we quantified the percentage of incident laser powers deposited into the bulk materials. Depending on the laser fluence, more than 50% of the incident power was transferred into the bulk of the copper specimen as heat.

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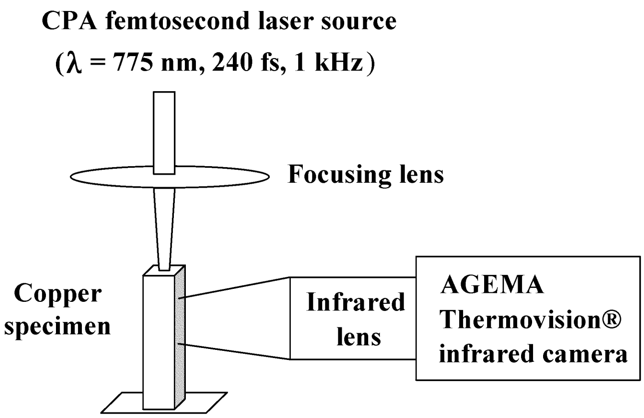

Fig. 1. Schematic of the experimental setup.

2. EXPERIMENTAL SETUP

The experimental set-up is shown in Figure 1. A Ti:sapphire fs laser (Clark-MXR, Inc., Dexter, MI; CPA-2001, central wavelength $\lambda = 775$ nm, at 1 kHz repetition rate, TEM_{00}, and ~240 fs measured at full width half maximum (FWHM) by an autocorrelator (APE *PulseCheck*, Berlin, Germany)) irradiated the top of the copper specimen. The copper specimen was cut from a copper plate and had dimensions of ~1.4 mm × ~1.4 mm (in cross-section) × ~12 mm (in length). The multiple-pulse fs laser was employed to ablate the copper specimen through a focusing lens (f = 50 mm) but at out of focus position. The spot size of the laser beam at the off-focus position was about 0.3 mm in diameter. The copper specimen was painted black on the sides to enhance its emissivity for the infrared thermograph study. The temperature field along the specimen was captured by an infrared camera (AGEMA Thermovision® 900, Barnstaple, UK). The infrared emission recorded was converted to temperature readings by calibration of the camera with thermocouples on a similar specimen by performing separate heating experiments.

3. RESULTS AND DISCUSSION

By irradiating copper specimens with a single laser pulse at different fluences and observing their surface damages, the peak single-pulse modification threshold of copper was determined to be ~792 $mJcm^{-2}$. Figure 2 shows the SEM images of the copper ablated with multiple laser pulses for approximately 45 s (or 45000 pulses) at different levels of average laser power. Although the peak fluence of an individual laser pulse in our study was either below or above the single-pulse modification threshold of copper, the accumulation of multiple fs pulses at all the power levels investigated led to ablation of the copper specimen with craters observed.

Figure 2 shows the HAZ around the craters, which became larger with an increase in the laser power due to the Gaussian profile of the laser beam intensity. Compared to another study (Nolte *et al.*, 1997), the craters and the raised edges surrounding the holes shown in Figures 2b–2d are much more prominent. As the raised edges are mainly the accumulation of the re-deposited material of the laser ablated matter, the atmospheric condition plays an important part among other parameters (Preuss *et al.*, 1995). In Nolte's experiments, the laser ablation was conducted under a vacuum condition, which resulted in much reduced height of raised edges and prominence of craters and thus cleaner holes. Furthermore, the significantly higher number of laser pulses in our study (45000 pulses) than that used in Nolte's experiment (5000 pulses) also contributed to the increased crater height. The combined factors of higher number of pulses and ablation in air explained the formation of the more prominent craters surrounding the holes in Figures 2b–2d.

To study the heat flow into the bulk material during the ablation process, we measured the temperature field along the copper specimen using an infrared thermograph technique. The power levels for the study of the heat flow into the copper specimen are slightly different from those of the SEM images (Fig. 2) as separate experiments were performed. However, from the SEM images in Figure 2, the copper was ablated with power as low as 71 mW. As all the powers employed for the heat flow study were larger than this power (i.e., 71 mW), ablation occurred for all the copper specimens for heat flow study.

Figure 3 shows the temperature gradient along the copper specimen under steady state condition. At a region close to the irradiated spot, the temperature distribution can be expected to be three-dimensional and the heat losses were due to convection and radiation at the top surface. Therefore, the temperature in the region less than ~0.35 mm from the irradiated spot was less than the maximum temperature, which occurred at a position of ~0.35 mm. Further away (i.e., greater than 0.35 mm) uniform temperature over a given cross section could be assumed, thus satisfying the requirements of one-dimensional (1D) heat conduction. For ease of understanding, and to simplify subsequent calculations, in both the transient and steady state analyses, only regions beyond 0.35 mm were analyzed. This does not have any impact on the conclusions, except an underestimation of the deposited thermal power as heat loss less than 0.35 mm would be neglected.

In our previous study for silicon specimens (Tran *et al.*, 2006), for a given laser power, the thermal power determined in the saturated condition (or steady state condition) was investigated first as it was judged that in general the steady state condition was more reliable. Subsequently, using the same thermal power, the predictions of the transient temperature distributions at various axial locations at the given laser power were compared with experimental observations. The variation between predictions and experimental observations provided an assessment of the reliability and accuracy of the thermal power determined from the steady state condition.

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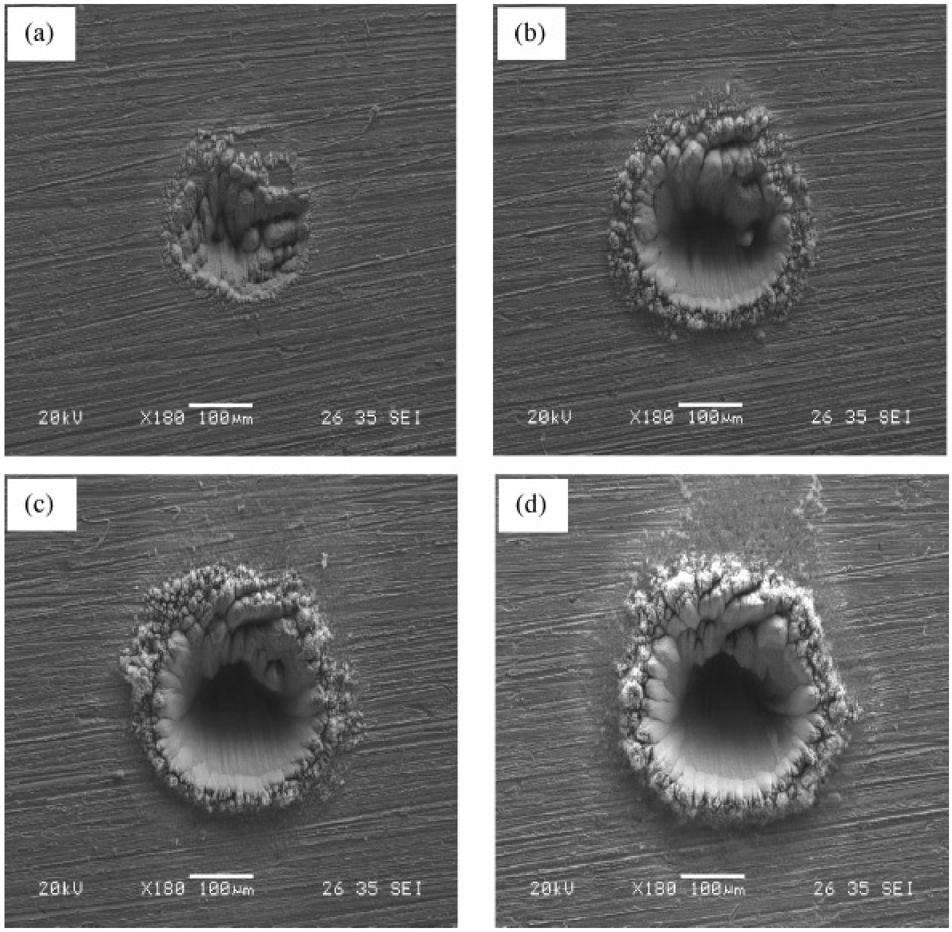

Fig. 2. Typical SEM images of copper specimen at different laser powers (spot size of 0.3 mm in diameter): (**a**) 71 mW, (**b**) 123 mW, (**c**) 176 mW, and (**d**) 247 mW.

For the current investigation, due to its high thermal conductivity, the temperature gradient along the copper specimen under steady state condition was nearly flat (see Fig. 3). With a lack of a significant temperature gradient, and a relatively short copper specimen (less than 10 mm), the experimental variation in temperature measurements had the potential to introduce significant noise for the estimation of thermal power deposited into the specimen from steady state condition. As a result, in this study, we chose to obtain an estimation of the thermal power by analyzing the transient temperature distribution first (Fig. 4). The thermal power so determined for each given laser power was subsequently employed for predicting the temperature profile under steady condition. A comparison between the steady temperature profiles predicted and obtained experimentally would provide added validation of the thermal power determined from the transient condition.

Figure 4 shows the transient temperature profile along the copper specimen. While Figure 4a shows the temperature profile at a fixed location (about 4.05 mm from the top of the specimen) at different power levels, Figure 4b shows the transient temperature profile at a particular power (467 mW) for two typical axial positions (0.35 mm and 8.07 mm) along the copper specimen. Transient temperature profiles at other axial positions are similar and as expected. Indeed, all these profiles were close together due to the high thermal conductivity of copper.

The solid lines in Figure 4 were obtained by simulating the transient heat flow of the specimen as a 1D heat problem. A constant power source was applied at one end and a prescribed temperature (as measured by the infrared camera) at the other (far) end of the specimens, taking into consideration of conduction, convective and radiative heat losses along the specimen to the environment (air, ~20°C). The thermal properties for the simulation study were taken to be temperature-dependent. At $T = 300$ K, the values of the density ρ, the thermal conductivity k and the specific heat c_p are 8950 kg/m^3, 401 W/mK, and 385 J/kgK, respectively. Depending on the temperature, the total heat loss coefficient (including both convective and radiative coefficients) varied from 17.3 W/m^{2}K to 22.9 W/m^{2}K. The total heat flow deposited into the specimen included the power for heat deposited into the specimens by conduction and the power for heat losses along the specimen to the environment by

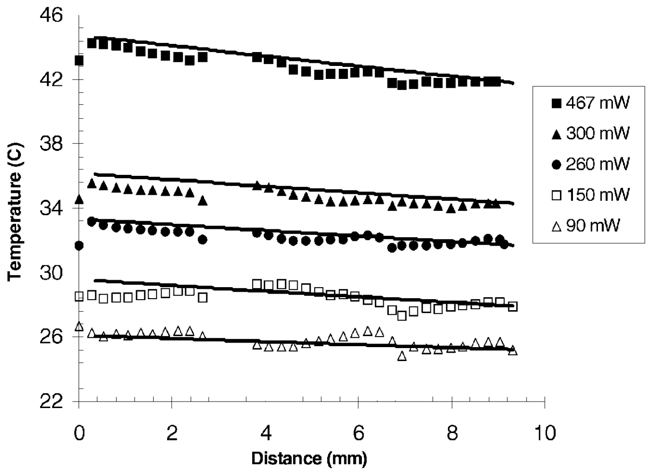

Fig. 3. Steady state temperature profiles along copper specimen at different incident laser powers (symbols are experimental data and solid lines are predictions from simulation study).

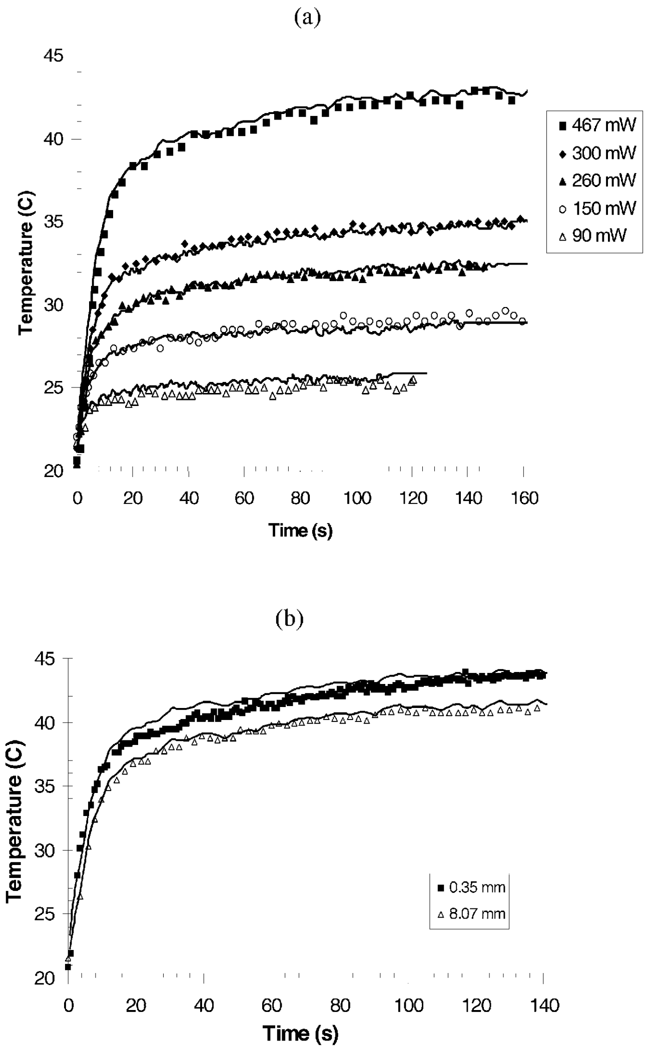

Fig. 4. Temperature profiles on copper specimen (**a**) at position of 4.05 mm from top of specimen for different incident laser powers and (**b**) at different positions along copper specimen for incident laser power of 467 mW (symbols are experimental data and solid lines are best fit curves from simulation studies).

convection and radiation. From the temperature profiles and the boundary condition, the total power for heat flow was calculated.

Figure 4 shows an excellent correlation of the transient temperature profiles between simulations and experiment studies, indicating that the deposited thermal power so-determined were reliable. Similarly to the previous study for silicon (Tran *et al.*, 2006), we observed the squiggles in Figure 4 presented in the transient temperature profiles. This is because of the fluctuation of the time-dependent temperature boundary condition at the far end as measured by the infrared camera.

The solid lines in Figure 3 shows the steady state temperature profiles predicted at different laser powers by employing the thermal powers determined from transient analyses. Figure 3 shows good agreements between experimental and simulated results, indicating the thermal power levels so-determined are reliable. Depending on the laser power, a saturated condition (with negligible temperature fluctuation with time) was achieved after laser irradiation between 120 s to 160 s. At the repetition rate of 1 kHz, the saturated condition occurred at about 120000 to 160000 laser pulses correspondingly.

Similar to the previous study for silicon, our results indicate that a substantial amount of the incident laser power was deposited into the copper specimen instead of being carried away by the ablated materials for all the cases investigated. Table 1 shows that for laser power with peak fluence higher or closes to the peak single-pulse modification threshold of copper ($\sim$792 mJcm^{-2}), approximately 50% of the thermal power was deposited into the bulk material. With a decrease in laser power such that its peak fluence was much lower than the peak single-pulse modification threshold, the thermal power deposited into the bulk material increased to over 77%. We speculate that as the laser power decreased significantly below the single-pulse modification threshold, there would be much less ablation, and thus less proportion of the laser power consumed in ablating the material. Instead, more proportion of the laser power would be converted to thermal power deposited into the material.

The interaction of a single fs laser pulse with metals is generally described by the so-called two-temperature heat

Table 1. *Percentages of laser power for heat flow into the copper specimen at different laser powers*

Incident laser power (mW)	467	300	260	150	90
Peak fluence (mJcm^{-2})	1321	849	736	424	254
% of laser power for heat flow	50.3%	50.0%	50.0%	86.7%	77.8%

conduction equation (Anisimov *et al*., 1974): the electron temperature T_e and the lattice temperature T_i. This is because the fs laser pulse duration is less than the electron–lattice relaxation time, which is in the order of 10 picosecond for metals (Chichkov *et al*., 1996). Due to the short pulse duration and high laser intensity of the fs laser, most of the laser energy is first transmitted to the electrons subsystems. The electron temperature T_e is therefore first heated to a very much higher temperature as compared to the ion (lattice) temperature T_i. However, the electron heating process only takes place within about 10^{-13} s (100 fs) after the laser pulse. After a longer period of time, the ion temperature T_i is eventually heated up and it could last for a longer period of time. As such, when multiple-pulse fs laser irradiates on the solids, we expect that over a comparatively much longer time period, energy could eventually transfer to the solids as deposited thermal power and cause thermal effects such as the HAZ or thermal energy dissipated into the solids. Although our study is on the heat transfer from the laser source to the substrate over a long time scale as compared to the duration of a single laser pulse, the energy of this heat transfer will have to come from the laser source. Our results indicated that the proportion of power from the laser source ended up as deposited thermal power in the substrate is substantial (more than 50%).

4. CONCLUSIONS

We report a simple yet reliable method for direct *in situ* observation of the temperature field in copper specimen ablated by multiple fs laser pulses. The results are consistent and comparable with our previous study for silicon and showed that more than 50% of the incident laser power is deposited into the solids as thermal energy. The results further indicate that thermal effect is important in femtosecond laser processing.

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