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INVESTIGATION AND ANALYSIS OF LASER BEAM MACHINING

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ABSTRACT

The high intensity which can be obtained by focusing the pulsed energy emitted by a LASER can offer potential as a tool for nearly forceless machining. The method can be used on any material, regardless of thermal properties, which can be evaporated without decomposition, including almost all ceramics and metals. With most substances, almost all of the material removed by LASER machining leaves in the liquid state. Only a small fraction is vaporized, and the high rate of the vaporization exerts forces which expel the liquid metal. All features of LASER beam machining improve with increased intensity. The higher the intensity, the less heat is resonant in the uncut material, an important consideration with materials which are sensitive to heat shock, and the more efficient the process is in terms of volume of material removed per unit of energy. The intensities which are available with the LASER are high enough so that the heat affected zone (HAZ) on a cut surface is too small to be detected and there is no solidified liquid film residue on the cut surface. In this paper Laser micromachining of an aluminum film on a glass substrate is investigated using atime-resolved transmission imaging technique with nanosecond resolution.

KEYWORDS: LASER, Aluminum Film, Laser Beam Machining (LBM)

INTRODUCTION

Laser beam machining (LBM) is an unconventional machining process in which a laser is directed towards the work piece for machining. Since the rays of a laser beam are monochromatic and parallel it can be focused to a very small diameter and can produce energy as high as 100 MW of energy for a square millimeter of area. It is especially suited to making accurately placed holes. The mechanism by which a LASER beam removes material from the surface being worked usually involves a combination of melting and evaporation, although with some materials, such as carbon and certain ceramics, the mechanism is purely one of evaporation. Any solid material which can be melted without decomposition can be cut with the LASER beam. Advances in nanotechnology motivate the extension of LASER machining of microstructures to the smaller dimensions of interest. Optical LASERs such as RUBY LASERs and CO2 LASERs are widely used for micro-milling and micro-hole drilling over a wide range of materials.

The size of the smallest features that can be created focusing intense LASER beams onto materials is limited mainly by the LASER wavelength and by the diffusion of heat. A variety of different techniques have been developed to overcome the limitations imposed by the diffraction limit in order to produce ablation craters of sub-wavelength size using optical and UV-LASERs. Nowadays, there have been several experiments over a wide range of LASER applications for material removal and cutting in which UV-LASERs and femto-second LASERs are the most popular for industrial use.

Also efforts have been made to minimize the tapers and HAZ which result due to high temperature of the LASER beam.It can be used to perform precision micro-machining on all microelectronic substrates such as ceramic, silicon, diamond, and graphite. Examples of microelectronic micro-machining include cutting, scribing & drilling all substrates, trimming any hybrid resistors, patterning displays of glass or plastic and trace cutting on semiconductor wafers and chips. A pulsed ruby laser is normally used for developing a high power.

Micromachining of metal films on a substrate is important for many applications, including photovoltaic devices, transparent conductors for displays, and microelectronics and sensor manufacturing. Short pulse-width lasers, such as nanosecond lasers, are often used in order to limit the thermal diffusion length and the resulting heat affected zone. During nanosecond laser ablation thermal processes such as melting, surface tension-driven flow, vaporization, and boiling can occur, all on a nanosecond time scale. Due to the short time scale and the lack of generalized equipment for measuring these processes, the temporal evolution of laser ablation is still under investigation.

Femtosecond (fs) lasermicro-machining is a widely used method to create features on surfaces. After its introduction almost 20 years ago, it has become a promising technique to obtain a desired surface topology. Homogenous surface structures on the micro-scale are necessary for the application of fs-laser micro-machining when aiming for reproducible results in topology-sensitive fields like anti-wetting or microfluidics. Thereby, superhydrophobic metallic surfaces obtained from fs-laser micro- machining have been shown to be advantageous to control phenomena like ice-friction.

PRINCIPLE

LBM uses the light energy of a laser beam to remove material by vaporization and ablation. The laser beam is focused for cutting. All its power is bundled onto one point, usually with a diameter of less that half a millimeter. Where the focused beam strikes the workpiece, the metal immediately begins to melt. It even partly burns or evaporates.

In this process the energy of coherent light beam is focused optically for predecided longer period of time. The beam is pulsed so that the releasedenergy results in an impulse against the work surface that does melting andevaporation. Here the way of metal removing is same as that of EDM process butmethod of generation of heat is different. The application of heat is very finely focused in case of LBM as compared to EDM.

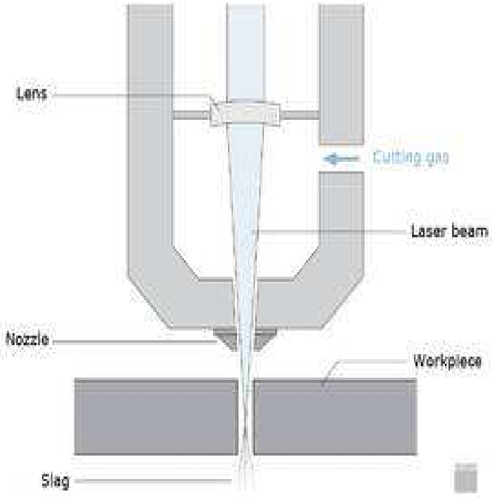

Figure 1: The Principle of Laser Cutting [1]

After a short time, the laser beam penetrates the material completely. The real cutting begins after this penetration. The laser beam moves along the contour of the part and melts the material as it advances. Molten metal and slag are blown away in a downward direction. This creates a narrow cutting gap that is barely wider than the focused beam itself.

Figure 2: Melting, Burning, Evaporating, Blowing - and Still the Human Eye Only Sees a Cutting Head Moving over the Sheet Metal [2]

In cutting, the laser beam processes the sheet, contour for contour.Notches in the part are always cut before the outer contour. The processing of each contour begins with piercing. The point where the sheet is pierced generally lies a little removed from the contour, in the scrap skeleton. In thicker sheets, material is thrown upward when the sheet is pierced, and the point of penetration is wider than the later kerf.After penetration, the laser beam first cuts until it reaches the contour and only then begins to cut the actual contour. To blow metal melt and slag out of the kerf, a cutting gas is blown into the slit under pressure. The type and pressure of the gas have a great influence on the cutting process and the cutting result.

When LASER hits the material surface, it will have some recoil force. It can drive the liquid away from the sides. Short pulsed LASERs generate higher recoil and it results in farther liquid removal. UV LASER will generate high temperature on material, and removed material gets ionized. This will form plasma in the hole. Plasma can absorb further incoming LASER energy. Part of it gets reemitted in wide spectrum and wide angle. It help the LASER energy coupling to material and also resulting in a larger "heat affected zone".

METHODOLOGY

Laser micromachining of an aluminum film on a glass substrate is investigated using atime-resolved transmission imaging technique with nanosecond resolution. Micromachining is performed using a 7 ns pulse-width Nd:YAG laser operating at the 1064 nm wavelength for fluences ranging from 2.2 to 14.5 J/cm2. A nitrogen laser-pumped dye laser with a 3 ns pulse-width and 500 nm wavelength is used as a light source for visualizing the transient hole area. The dye laser is incident on the free surface and a CCD camera behind the sample captures the transmitted light. Images are taken from the back of the sample at various time delays with respect to the beginning of the ablation process, allowing the transient hole area to be measured. For low fluences, the hole opening process is delayed long after the laser pulse and there is significant scatter in the data due to weak driving forces for hole opening.

However, for fluences at and above 3.5 J/cm2, the starting time of the process converges to a limiting minimum value of 12 ns, independent of laser fluence. At these fluences, the rate of hole opening is rapid, with the major portion of the holes opened within 25 ns.

The second stage of the process is slower and lasts between 100 and 200 ns. The rapid hole opening process at high fluences can be attributed to recoil pressure from explosive phase change. Measurements of the transient shock wave position using the imaging apparatus in shadowgraph mode are used to estimate the pressure behind the shock wave. Recoil pressure estimates indicate pressure values over 90 atm at the highest fluence, which decays rapidly with time due to expansion of theablation plume. The recoil pressure for all fluences above 3.1 J/cm2 is higher than that required for recoil pressure driven flow due to the transition to explosive phase change above this fluence.

The experimental apparatus is shown in figure 3.

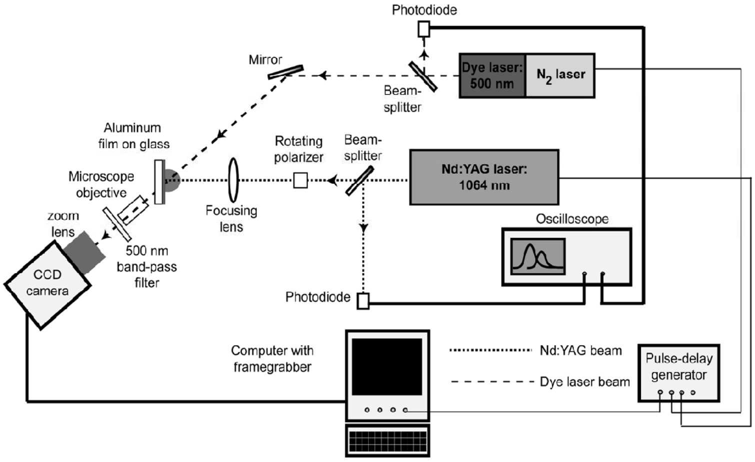

Figure 3: Experimental Apparatus [3]

Ablation isinduced by an Nd:YAG laser with a pulse duration of 7 ns at fullwidth half maximum (FWHM) operating at the fundamentalwavelength of 1064 nm. The spatial irradiance profile deviatessomewhat from an ideal Gaussian profile with M2¼6. The Nd:YAG beam energy is adjusted using two rotating beam polarizers and focused to a diameter of 63 lm on the film. The 200 nm aluminum films were deposited on glass substrates by dc magnetron sputtering. A nitrogen laser-pumped dye laser tuned to a wavelength of 500 nm is used to illuminate the sample surface for time-resolved transmission imaging. The pulse width of the dye laser is approximately 3 ns (FWHM), which provides the short time resolution for imaging.

The Nd:YAG and dye lasers are triggered by a time delay generator which allows the delay between lasers to be controlled with nanosecond resolution. Photodiodes are used to physically measure the actual time delay between the two laser beams since the actual delay varies from pulse to pulse due to jitter in the delay generator and the lasers' electronics. The actual time delay is also calibrated by correcting for the time required to travel the physical path length between each photodiode and the sample. The sample is viewed from the backside,such that only transmitted light is captured. The images are dark until the ablation process begins to perforate a hole in the film, allowing some of the dye laser beam to reach the CCD.

The experiments are performed with single laser shots in ambient air, and each ablation shot is performed in an undamaged location of the film. The images for each ablation shot are taken at two different times, one at the specified time delay and the other one long after the ablation laser shot (seconds after ablation). The second image is taken such that the transient hole area can be compared to the final hole area. This allows variations in hole diameter, due to pulse-to-pulse variations in the laser beam energy, to be monitored.

A sequence of snapshots for different times, for a laser fluence of F¼12.2 J/cm2 is shown in figure 3. The images are analyzed by sharpening the edges, defining the gray thresholds, and counting the number of pixels. MATLAB VR is used for image analysis and edges are sharpened with the “Unsharp” filtering function. In order to use the filter, the “gray threshold” is set to a value ranging from 0.5 to 0.7 (on a scale of 0 to 1; 0 represents black and 1 represents white) depending on the ambient conditions. Experiments were taken at different times during the day; thus, the background light and hence the gray threshold varied. Thus, for a given fluence, all images were taken within a short time period to avoid variations in gray threshold for a given data set. The image analysis was performed manually and a proper gray threshold was determined for each fluence. The camera makes an angle with the back side of the film (ranging from 40 to 50 deg), and hence the pixel lengths on the horizontal and vertical directions do not represent the same length scales. The length of the pixels were calculated by manually.

RESULTS AND DISCUSSIONS

Damage to the films, due to melting, was observed at a thresholdfluence of 1.8 J/cm2. The first holes were opened at a fluence of 2.2 J/cm^2, with an average final radius of 13 µm. Between 1.8 and 2.2 J/cm^2, observation of the films under an optical microscope revealed increasing levels of damage due to melting and vaporization without opening a hole in the film.Figure 4is a plot ofthe final radius of the holes as a function of laser fluence above the threshold for hole opening. Figure 5shows an optical microscope image of holes formed at 2.6 and 6.6 J/cm2, each of which shows the melt rim at the edge of the hole that results from the radial motion of liquid. Additionally, ejected melt can be observed at the surrounding edges of the hole.

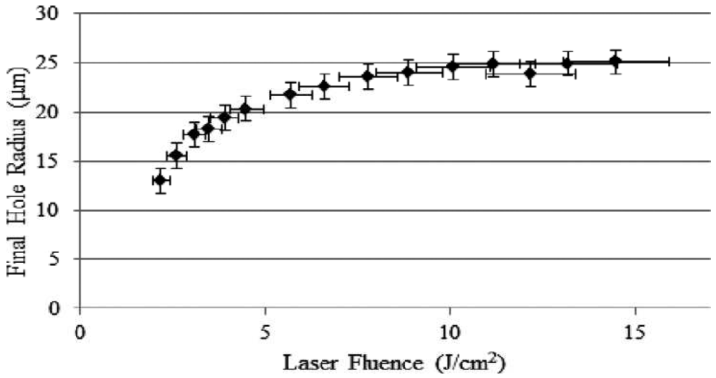

Figure 4: Final Radii of Opened Holes Measured by Imaging Apparatus [4]

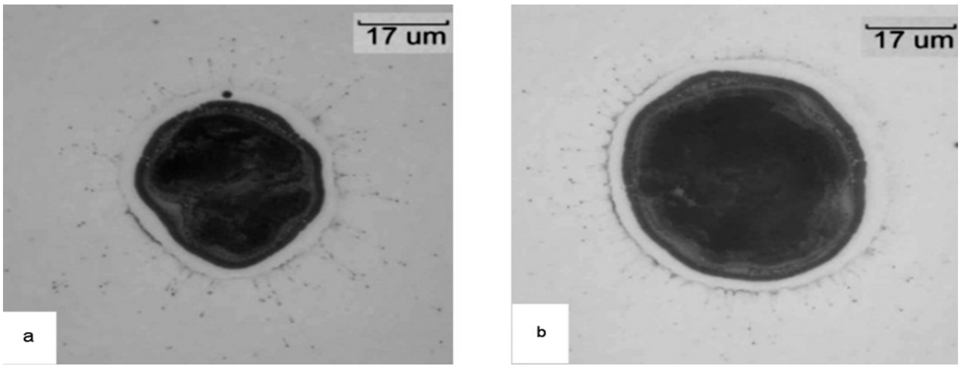

Figure 5: Optical Micrographs of Holes Formed at (a) 2.6 and (b) 6.6 J/cm^2 [4]

The square of the ratio of the transient radius to the final radius(REq./REq.,1)2, is plotted as a function of the time, t, in Figure 6. At the lowest fluence, 2.2 J/cm2, holes do not begin to open until 52.4 ns. Since this fluence is only slightly above the ablation threshold of 1.8 J/cm2, it is expected that Marangoni effects and some vaporization are responsible for the hole opening process. The delay in hole opening is consistent with Marangoni-based hole opening, which is slow to develop. At the next higher fluence, 2.6 J/cm2, the hole opening process begins much earlier, as early as 20 ns. However, at this fluence there is significant scatter in the data, likely due to the fact that the fluence is close to a transition point. As will be discussed shortly, above 3.1 J/cm2 a much more rapid and repeatable hole opening process is observed with lower scatter in the data as the fluence increases. Thus, for 2.6 J/cm2, scatter is likely due to the fact that it is near a transition pointin the hole opening process.

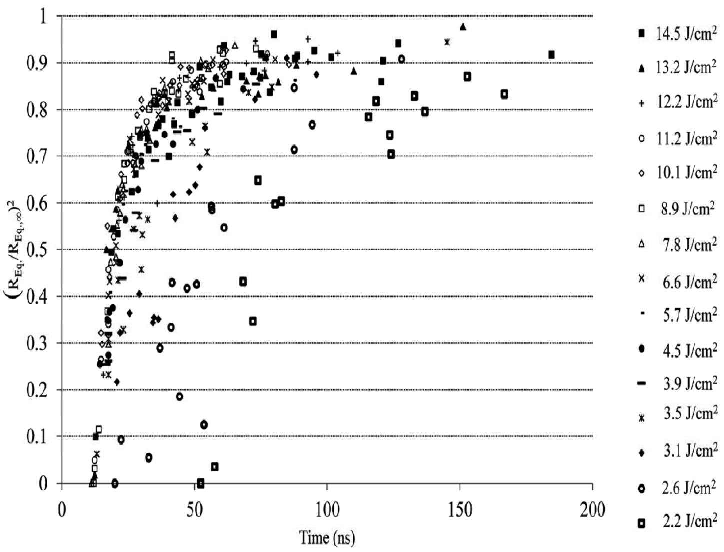

Figure 6: Square of the Ratio of the Equivalent Radii of the Hole during Opening and the Hole Long after Being Opened [5]

Results of the authors work showed that the laserheated region was ablated by phase explosion, with a transition to vapor phase completed in less than 15 ns for the highest fluences. In the present work we believe that while some of the material is certainly removed directly to the vapor phase by phase explosion, this cannot account for the entire hole opening by a single laser pulse. In Figure 5, the characteristic rim of displaced melt that results from radial melt flow was observed, which would not occur if the material was simply vaporized. It is more likely that the observed hole opening is a combination of processes for fluences above 3.1 J/cm2, although the distinction between material removal due to phase explosion and melt displacement due to phase explosion-induced recoil pressure cannot be distinguished in the current experiment. Below this fluence weak recoil pressure due to normal vaporization and Marangoni effects are responsible for the slower hole opening process.

CONCLUSIONS

In several investigations, Laser micromachining process of aluminum film was studied with a nanosecond transmission imaging apparatus. The hole opening followed a two-stage process. It was generally observed that holes opened rapidly after the laser heating due to high vapor recoil pressure, with most of the hole area opening within a short duration after the beginning of laser irradiation.

The first stage of rapid hole opening was attributed to the high recoil pressure above the aluminum surface, due to phase explosion above a certain cut-off fluence. As the pressure decreased, and the material plume exceeded the diameter of the laser spot, the hole opening proceeded more slowly and was likely the result of surface-tension effects. Therefore, this analysis has generated new knowledge on experimental analysis of laser beam machining for a wide variety of conditions.

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