HYDRODYNAMIC THIN FILM DRILLING USING CONTINUOUS WAVE LASER-INDUCED BUBBLES

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RESUMEN
Debido a su bajo costo, las burbujas de cavitation inducidas por un láser de onda continua (CW, por sus siglas en inglés) de baja potencia ofrecen una alternativa interesante para la fabricación de estructuras (orificios y canales), en comparación con la ablación láser con pulsos cortos y ultracortos de alta intensidad. El propósito de este trabajo es estudiar la dinámica de las burbujas de cavitation inducidas por un láser CW para entender los mecanismos que dañan películas delgadas. Se presentan los resultados experimentales basados en fotografía de alta velocidad de las burbujas inducidas por el láser CW con tiempo de resolución de 7 μs por cuadro. Se encontró que las burbujas inducidas entre dos fronteras sólidas disminuyen sus radios y su tiempo de oscilación mientras la potencia del láser aumenta. En contraste con las burbujas inducidas sin fronteras sólidas cercanas, estas burbujas no presentan expansión y colapso repetitivo. Las velocidades máximas de expansión y colapso de los radios superior e inferior son de magnitud similar. Los esfuerzos cortantes originados dentro del campo de flujo alrededor de las burbujas oscilantorias se han calculado numéricamente obteniendo un valor máximo de 9500 Pa. Imágenes del Microscopio Electrónico de Barrido (MEB) muestran regiones totalmente limpias de material de película delgada y bordes limpios, que se puede tomar como indicador de la buena calidad de micromaquinado que es posible obtener con este método.

Palabras clave: burbujas de cavitation, láser de onda continua (CW), fotografía de alta velocidad, tiempo de oscilación, película delgada.

ABSTRACT
Because of its lower cost, low power continuous wave (CW) lasers offer an interesting alternative for manufacturing structures (holes and canals), compared with laser ablation with short and ultrashort high intensity laser pulses. The purpose of this work is to study CW laser-induced cavitation bubble dynamics to understand the mechanisms of thin film damage. We present experimental results based on high speed photography of CW laser induced bubbles with time resolution of 7 μs per frame. It was found that such bubbles induced between two solid boundaries present decreasing radii and oscillation times with increasing laser power. In contrast with bubbles induced with no near boundaries, these bubbles do not show repetitive expansion and collapses. The maximum expansion and collapse velocities for the upper and lower radii are of similar magnitude respectively. The shear stresses originated within the flow field around the oscillating bubbles have been numerically calculated to have a maximum value of 9500 Pa. SEM imaging revealed regions totally clean from thin film material and sharp edges, which can be taken as indicator of the good quality micropattering that is possible with this method.

Keywords: Cavitation bubbles, Continuous wave (CW) lasers, High speed photography, Oscillation time, Thin film.

1 INTRODUCTION
Thin films are layers of materials that are deposited on the surface of a substrate. Typically, its thickness varies from few hundreds of nanometers to several micrometers [1-3]. Common materials for thin films are metals such as aluminum, brass, titanium, alloys, polymers and ceramics. Deposition of thin films is important due to its application in transistor technology, design of semiconductor electronic equipment, optical coatings and many more. Thin film micropatterning is a process used for electronic circuit manufacturing.
Thin film micropatterning is a manufacturing process of structures such as canals and holes for a specific goal on thin films. Modern techniques involve laser ablation using high intensity short and ultrashort laser pulses. Applications of thin film micropatterning are found from medicine to electronics. Femtosecond laser pulses have been successfully used to ablate surfaces with edges free of redeposited material. In contrast, nanosecond and picoseconds laser pulses produce ablation with significant thermal damage and redeposited material around the ablated area.

Cavitation bubbles can be produced by optical, acoustical or hydraulic means. It is well known that cavitation bubbles expand and collapse several times until the bubble disappears. After each bubble collapse, a shock wave with amplitude up to megapascals is produced and the bubble expands again.

It is well documented that when a sufficiently intense short (< μs) or ultrashort (< ns) laser pulse (for a certain pulse energy, the shorter the pulse the more intense it is) is tightly focused in the bulk of an aqueous media, the laser pulse energy is nonlinearly intense it is) is tightly focused in the bulk of an aqueous media, the laser pulse energy is nonlinearly absorbed originating material ionization that leads to hot expanding plasma formation [4-6]. The plasma is the responsible mechanism for which compressive shock waves are generated in the material surrounding the plasma and ultimately lead to the formation of an oscillating bubble [4]. Bubble expansion and collapse originate a flow field around it. When this occurs near a solid boundary, the shock wave and the bubble [7, 8] interact with the boundary producing normal and shear stresses on the boundary surface. These stresses induce mechanical but quite predictable damage on surfaces [8]. A very important parameter for the bubble dynamics interacting with a solid boundary is the parameter γ, which is given by γ=z/R_{max}, where R_{max} is the maximum bubble radius and z is the distance between the boundary and the bubble center [8]. Although bubbles can be induced by purely acoustic methods, laser-induced bubbles have the unique characteristic that they can be positioned with a precision within 20 μm, which is the typical lens’ Rayleigh range used previously [9, 10].

There is evidence that pulsed laser surface ablation efficiency is enhanced when it occurs in a water-confined environment [11-15]. In previous studies, a silicon surface has been placed under water and up to 1000 laser pulses, 248 nm wavelength, 23 ns pulse duration delivered positioning the beam’s waist right on top of the surface and compared the results when the irradiation is carried out in air [12]. It has been found that: (a) the water layer over the surface must have an optimal thickness to avoid laser light absorption along the beam’s optical path before the beam’s waist. (b) Presence of water avoids re-deposition of ablated particles. (c) Morphology of ablated surface is different under water than in air due to the laser-induced water movement. (d) Water cooling, plasma shielding and dissolving effects are factors that also affect laser ablation [14].

It has been recently demonstrated that it is possible to generate cavitation bubbles focusing a relatively low power (<150 mW), continuous wave (CW), near infrared laser in a solution of copper nitrate, which has a high linear absorption coefficient (160 cm⁻¹) for a saturated solution) at the used wavelength [16]. Bubble dynamics of CW laser-induced bubbles is significantly different than those induced by pulsed lasers: (a) due to high linear absorption of the solution, they can only be generated near the liquid surface from which the beam is incident and hence have semispherical shape; (b) bubble generation is periodic and bubble frequency of generation increases with laser power while bubble size and oscillation time decrease. Using such CW lasers to generate cavitation bubbles in a controlled way, offers an alternative to fabricate microstructures onto thin solid films between one and two orders of magnitude less expensive, compared to bubbles produced with high intensity pulsed lasers [17]. For these bubbles to interact with the thin film, it is required to induce them within an absorbing solution volume such that its height is comparable with the bubble size.

In this work we present an experimental study of the dynamic behavior of CW laser-induced bubbles between two solid boundaries. The specific objective is to experimentally study the thin film erosion phenomena generated on metallic thin films by the interaction of the fluid mechanics associated to an oscillating laser-induced bubble near the thin film’s surface in a saturated copper nitrate solution-confined environment. The underlying hypothesis is that the shear stresses originated by the oscillatory flow field around a bubble induced by continuous wave laser and the shock wave launched upon its collapse, near a solid boundary are strong enough to produce metallic thin film damage. Finally we show a Scanning Electron Microscope (SEM) picture of a 100 nm thick molybdenum thin film drilled by laser induced cavitation bubbles.

2 MATERIALS AND METHODS
2.1 Experimental apparatus

Figure 1 shows the proposed experimental model to study thin film erosion. It consisted of a thin film to be studied deposited onto a glass substrate covered with a copper nitrate solution layer and a cover slip that encloses the fluid; a CW (λ=975 nm) laser was tightly focused and incident from above the cover...
slip. The fundamental requirement was that the thickness of the copper nitrate layer that covers the thin film to be eroded be comparable to the bubble size. The reason for this is that the linear absorption coefficient of a saturated copper nitrate solution (160 cm$^{-1}$ at the laser wavelength) produces a penetration depth of 62.6 μm and therefore laser light was highly attenuated near the surface from which the beam was incident; moreover, the beam’s waist diameter was 30 μm and positioned 100 μm below the copper nitrate surface; hence the interaction volume where the bubbles were formed was in that order of magnitude. The cavity for the copper nitrate solution was made using spacers 0.120, 0.240 and 0.360 mm thick.

Figure 1 shows the experimental apparatus to study thin film erosion due to cavitation bubbles induced with a CW laser in an absorbing solution.

Figure 2 shows the experimental set-up used to study bubble dynamics between two solid boundaries. The laser used was a diode laser that emits at $\lambda=975$ nm and maximum power of 400 mW. The laser can be modulated by means of a function generator to produce laser pulses as short as tens of microseconds. The laser beam was brought to the target through mirrors M1 to M5. Laser power was adjusted using optical density (OD) filters. Laser power was monitored directing a portion of the beam using a beam splitter (BS) to a power monitor (PM) previously calibrated against a second power meter positioned at the targets position. The beam was focused inside the copper nitrate solution using a 6 mm focal length and 0.5 NA aspheric lens (LC). Because the life time of cavitation bubbles is less than 500 μs, a video system with such time resolution was required. We used a high speed camera (HSC) adjusted to acquire images at 7 μs per frame.

2.2 Numerical Simulation

The shear stress generated on the thin film due to the flow field is calculated by numerical simulation using COMSOL software. Because the system geometry involves a separation between boundaries $d$, that is much smaller than the length $L$, we proposed the computational domain as a very long channel with a moving wall on the left and fully developed flow on the right (see Figure 3). In such a system, the bubble boundary is modeled as a solid vertical wall moving to the right with velocity $u_r(0)$ taken from high speed experimental data and the boundary on the right does not affect the flow field.

As shown in high speed photography, the bubble acquires a disk-shape that expands and collapses symmetrically in radial direction. Therefore, the modeling is carried out using an axisymmetric cylindrical coordinate system. The fluid is assumed to be incompressible, newtonian with constant properties of water at 20 °C. The no slip boundary conditions $u_r=0$ and $u_z=0$ are applied to the upper and lower boundaries.

Using a uniform refined mesh with element size between 4.2×10$^{-6}$ m and 1.2×10$^{-6}$, the domain has been covered by a mesh of 11,230 triangle elements. The calculations have been carried out with the direct solver PARDISO, Comsol 4.2 and the time step has been set by the solver.

The fluid flow is described by the continuity (Equation 1) and Navier-Stokes equations (Equation 2):
2) for an incompressible fluid which are solved for the velocity field \( \mathbf{u} = (u_r, u_z) \) and pressure \( p \) [18]:

\[
\nabla \cdot \mathbf{u} = 0
\]

\[
\rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \mu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) + \mathbf{F}
\]

Where \( \rho \) is the density, \( \mu \) viscosity, \( \mathbf{I} \) the identity matrix and \( \mathbf{F} \) is a vector of volumetric forces. In our case we have no volumetric forces.

The shear stress of interest is produced on the lower wall where the thin film is located. It is calculated according to Newton’s law of viscosity (Equation 3) using velocity gradient of \( u_r \) with respect to the \( z \) direction, where \( \tau \) is the shear stress:

\[
\tau = \mu \frac{\partial u_r}{\partial z}
\]

2.3 Scanning Electron Microscope (SEM) imaging

The damage produced to our thin films was characterized using SEM imaging. The instrument used was a JSM-6610. The samples were imaged with 20 kV accelerating potential, 50 nm spot size, 30 \( \mu \)m aperture, at a working distance of 10 mm, and all images were backscatter electron images.

3 RESULTS AND DISCUSSION

3.1 Bubble dynamics experiments

Figure 4 shows a series of images obtained with the HSC where the expansion and collapse of a CW laser-induced bubble between two solid boundaries can be observed. In these images, the beam is incident from above. In a first stage, the bubble grows with a semispherical shape until the lower part of the bubble touches the lower boundary (thin film); then the bubble continues expanding in the lateral (radial) direction.

The bubble collapse deserves special attention because it has been documented that it produces shock waves, whose amplitude is in the order of megapascals. When the mixture of gas and vapor inside the bubble reaches its maximum volume, pressure inside is minimum and less than the static pressure outside it, which pushes the bubble wall inwards and produces the bubble collapse.

In Figure 4, the frame labeled with 105 \( \mu \)s, the arrows indicate the distances that we will refer as “upper radius” and “lower radius”. For the case shown in the figure, laser power was 106 mW and the separation between boundaries was 0.240 mm.

Figure 5 shows a time evolution of the upper and lower radii a function of time. Laser power was 106 mW and separation between boundaries was 0.120 mm. For these conditions, it can be observed that the lower radius reaches its maximum a few microseconds after the upper radius. In contrast with the case when bubbles are not confined between two boundaries, we didn’t see the multiple reexpansions and collapses that have been documented for plasma-induced bubbles. The time that takes for the bubble to form, expand and collapse is the oscillation time.

Figure 6 and 7 show the maximum bubble upper and lower radii as a function of the laser power while figures 8 and 9 show the oscillation time. Figure 7 shows lower radius data for the two shortest boundary separations because the bubbles were
smaller than the 0.360 mm separation. Both radii decrease with laser power and therefore the oscillation time too. Even though a previous study of this same kind of bubbles where the bubble is not confined [16] reports an exponential decay of the bubble size with laser power, such exponential decay is not clearly observed in our experiments.

Fig. 6 Bubble upper radius as a function of laser power for the three cases tested.

Fig. 7 Bubble lower radius as a function of laser power for two of the cases tested.

Fig. 8. Time oscillation upper radius as a function of laser power for the three cases tested.

Fig. 9. Time oscillation lower radius as a function of laser power for the two cases tested.

A two-way ANOVA ($\alpha=0.05$) was performed with the data for the upper radius as a function of laser power. The resulting $p$-values for the individual factors in the experiment (boundary separation and laser power) were both $<0.001$, while the $p$-value for the interaction between factors was 0.41. The $F$ value for both separation and power was higher than the $F$ critical value. Such parameters indicate that both boundary separation and laser power are statistically significant for the upper bubble radius. A summary of the statistical analysis is presented in table 1.

<table>
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<th>Table 1. Summary of statistical analysis</th>
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<td><strong>F</strong></td>
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Due to the fact that laser light penetration depth is half the smallest separation distance tested in these experiments, the energy coupled to the absorbing solution for each tested laser power value, produces bubbles originated by vaporization of the same water volume. If the bubble maximum volume is the same for each laser power, it is expected that the lower the separation between boundaries, the greater the bubble radii. In our experiments, even though the bubble radii for the 0.240 mm separation are always greater than those for the 0.120 mm separation, the radii for 0.360 mm separation overlap with those of the 0.120 mm separation. A feasible explanation is that it may be necessary to decrease the boundary separation even more to observe this phenomenon. It should be mentioned that 0.120 mm is the shortest boundary separation for which the illumination allowed to acquire the high speed videos.
Figure 10 shows bubble wall velocity calculated from the experimental information of the time evolution of the bubble upper and lower radii. For the case shown in the figure, laser power was 106 mW and the separation between boundaries 0.120 mm. When the bubble forms, it has a semispherical shape and only the upper radius exists. For further expansion, the lower part of the bubble touches the lower boundary and the lower radius forms and grows faster than the upper radius. The bubble acquires a disc-like shape whose radial boundary tends to become a vertical line as shown in frames labeled from 175 to 280 $\mu$s in figure 3. The maximum speed of both radii is very similar in the expansion and collapse.

![Figure 10](image10.png)

**Fig. 10** Expansion and collapse velocity of a bubble’s upper (dotted line) and lower radius (continuous line). Laser power was 106 mW and boundary separation 0.120 mm.

### 3.2 Numerically calculated shear stress

Figure 11 shows the shear stress as a function of the distance with respect to the axisymmetry axis for different times within the bubble’s life. The laser parameters used for the calculation in figure 11 are 106 mW and the separation between boundaries was 0.120 mm. The velocities fed to the model correspond to those shown in Figure 9. The maximum shear stress occurs at the wall during the bubble expansion (40 $\mu$s) and collapse (200 $\mu$s) due to the large change in the magnitude of velocity. The maximum shear stress obtained is 9500 Pa, below the yield strength of titanium for example, which is 700 MPa [19]. Young’s modulus for this film is 128 GPa.

![Figure 11](image11.png)

**Fig. 11** Shear stress as a function of position with respect to the symmetry axis at different times within the bubble lifetime. Laser power was 106 mW and separation between boundaries of 0.120 mm.

### 3.3 SEM imaging

Thin film damage was characterized with SEM imaging. Figure 12 shows a typical image of a molybdenum 100 nm-thick thin film exposed to cavitation bubbles induced by continuous wave laser. Laser power was 452 mW exposed during 1 second, which produced 345 bubbles. The separation between boundaries was 0.120 mm. The bright part is molybdenum and the dark area is the glass substrate from which molybdenum was removed. It is important to notice that the SEM image shows that the dark region is totally clean of molybdenum and presents sharp edges, which is an indicator of the good quality thin film micropatterning that this method can produce. Further research in in progress to fully characterize the material removal as a function of the laser and geometrical parameters.

![Figure 12](image12.png)

**Fig. 12.** SEM image of a continuous wave laser-induced damage to a 100 nm thick-molybdenum. Laser power was 452 mW and a boundary separation 0.120mm
CONCLUSIONS
CW laser induced cavitation bubbles within a linearly absorbing solution between two solid boundaries increase size and oscillation time for decreasing laser power and do not present multiple expansion and collapses. Such bubble dynamics is significantly different compared to plasma mediated bubbles which increase its size and oscillation time with laser pulse energy and present multiple reexpansions upon collapse. Maximum speed of upper and lower radii of approximately the same magnitude and happen soon after bubble initial growth and bubble. SEM imaging showed good quality thin film micropattering was possible with the presented method.

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REFERENCES
2. V.P. Sondankar and G.N. Chaudhari, OAM-RC. 1, 520-522 (2007)
9. N. Bremond, M. Arora, S. M. Dammer and D. Lohse, Phys Fluids. 18, 1-10 (2006)