The International Society for Optical Engineering

SPIE Newsroom

10.1117/2.1200612.0534

Sound and light: acoustics play an unexpected role during laser machining

Sanghyun Lee and Alan Hunt

Physical theory helps to identify strategies for combating severely attenuated micromachining rates caused by debris formation.

The ultimate aim of micro- and nanofluidics is to construct micro total-analysis systems (μTAS), in which complex analytic processes are performed on a chip for simplified application, decreased costs, and minimal sample volumes. To realize this goal, complex micro- and nanofluidic networks must be integrated into a single chip. Moreover, achieving appropriate interconnection among components and high device density usually require 3D geometries. Thus, the advantages of conventional 2D planar lithography-etch-bond processes are offset by the difficulty of achieving true 3D geometries.

Laser machining using femtosecond pulses constitutes a promising method of 3D nanofabrication:[1–3] far-field optical ablation allows true 3D (rather than multilayer) geometries, while submicron feature sizes are still attainable using tightly-focused laser pulses operating in the optics-in-critical-intensity regime.[1] This takes advantage of the deterministic character of femtosecond laser machining[4] to achieve precise and reproducible ablation of nanofeatures inside and on the surface of glass or other transparent materials.

If machining is performed in liquids, it is possible to form long, open channels in a single step since debris is cleared from the channels by expanding bubbles produced during laser ablation.[3,5,6] However, like other, more conventional microdrilling methods, optical machining is limited in terms of the attainable aspect ratio (AR) of subsurface channels: debris extrusion becomes difficult as the machining progresses far into the material.[7] Similar to conventional microdrilling methods, femtosecond laser machining has been limited to AR < 100.[8]

By optimizing the machining protocols we were able to extend the AR somewhat, but found that the effectiveness drops precipitously at around AR = 300. This initially was ascribed to increased resistance to flow in longer channels, which predictably inhibits clearing of debris, and thus ultimately must limit reasonably attainable AR. However, repeated scans of the laser over AR = 300 abruptly and unexpectedly recovered machining effectiveness, thus enabling further lengthening of the channel. Moreover, even though the end of the channel resumed growing, the poor machining region around AR = 300 initially remained clogged with glass debris, and the channel appeared to be divided into two parts. With further scans of the laser, these two parts united, achieving a continuous longer channel.

Closer examination shows the localized regions of poor machining to be associated with dramatically changed bubble dynamics. When the AR is smaller than 300, vigorous bubble expansion effectively extrudes water-entrained debris out of the channel. However, as AR approaches 300, machining becomes inefficient, with both bubble expansion and debris extrusion becoming severely attenuated. Interestingly, a second region of poor machining is encountered when the channel becomes twice as long, suggesting harmonic phenomena. And indeed, we find evidence for a (to the best of our knowledge) hitherto unidentified form of acoustic node that presents an alternative acoustic pathway for the dissipation of absorbed laser energy, and consequently decreases the energy available for bubble expansion.

The acoustic AR barrier at 300 can be delayed either by using degassed water to assist femtosecond laser machining or by varying the ambient pressure during machining. This is predicted from a physical model in which acoustic nodes form when an internal two-phase (gas and water) flow forms a stable resonant structure. The impedance of the water and gas structures becomes matched, allowing deposited energy to readily dissipate across the fluid-gas interface, thus causing fluid circulation to fail due to a precipitous decrease in bubble expansion. The bubbles may even completely vanish, despite persisting for hundreds of milliseconds only a few microns away, where

Continued on next page

they move from the laser focus toward the channel mouth. This brings the machining progress to a near standstill, even with repeated sweeps of the laser over the difficult region. Fortunately, the channel lengths over which the acoustic nodes form are quite localized, and precisely controlled repetitive machining over the difficult regions can overcome the acoustic barriers. Moreover, by employing strategies such as degassing and pressure changes, described above, the acoustic barriers can effectively be delayed.

The analytic solution for the first acoustic node formation (node equation) is derived from the two frequencies of structural resonance and pressure oscillation, and shows that acoustic node formation is a function of internal pressure, temperature, and gas composition of the bubble. The gas composition of the bubble between the water plugs at the inlet and the dead end of the channel determines the speed of sound. It is most dependent on the mole fraction of H_2, which has a speed of sound almost four times faster than that of other primary gases, such as O_2 and N_2. Based on the analytic model, the mole fraction of H_2 in the gas plug is about 15% when water saturated with atmospheric gasses is used, whereas degassing water increases it up to 42%. The increase in H_2 delays acoustic node formation up to twice the channel length. Consequently, the acoustic AR barrier of 300 is delayed up to 600. The analytic model predicts that node position could be controlled by varying the internal pressure and temperature. To verify this, we custom-built a pressure controller and measured the effect of pressure on node formation. Our results were similar to that predicted by mathematical calculations.

After overcoming the first acoustic node, the maximum AR can be extended over 1000 before a second acoustic node is encountered. This makes it possible to develop analytic devices such as a nanocapillary-electrophoresis separation device, which requires a long separation channel.[9]

Understanding the role of acoustics during femtosecond laser machining provides a basis for creating complex micro- and nanofluidics with the freedom to arbitrarily configure components in three dimensions. This feature is critical for developing complex lab-on-a-chip and micro total-analysis systems. It also reveals the importance of parameters not generally considered in analyses of optical breakdown and laser machining, such as pressure, resonant structures, and acoustics. Not least, it provides a theoretical basis for attaining the full potential of laser machining for diagnostics, sensors, drug discovery, microreactors, and chemical analyses.

This work was supported by grants from IMRA Corporation and the NIH.

Author Information

Sanghyun Lee
Microfluidics Lab/ME
Cellular and Molecular Biomechanical Lab/BME
University of Michigan, Ann Arbor
Ann Arbor, MI

Sanghyun Lee was first author on a paper presented at a SPIE conference in Stockholm in 2006.

Alan Hunt
Biomedical Engineering
University of Michigan, Ann Arbor
Ann Arbor, MI
http://www.umich.edu/~huntlab/

Alan J. Hunt is director of the Biomedical Lab at the Center for Ultrafast Optical Science, and leads the Cellular and Molecular Biomechanics Laboratory in the Biomedical Engineering Department at the University of Michigan. He made an oral presentation on this work at a SPIE conference in Stockholm in 2006.

References

1. A. P. Joglekar, H. H. Liu, E. Meyhöfer, G. Mourou, and A. J. Hunt, *Optics at critical intensity: applications to nanomorphing*, **Proc. Natl. Acad. Sci. USA 101**, pp. 5856–5861, 2004.
2. A. J. Joglekar, H. H. Liu, E. Meyhöfer, G. Mourou, and A. J. Hunt, *A study of the deterministic character of optical damage by femtosecond laser pulses and applications to nanomachining*, **Appl. Phys. B: Lasers Opt. 77**, pp. 25–30, 2003.
3. K. Ke, E. F. Hasselbrink, and A. J. Hunt, *Rapidly prototyped three-dimensional nanofluidic channel networks in glass substrates*, **Anal. Chem. 77**, pp. 5083–5088, 2005.
4. D. Du, X. Liu, G. Korn, J. Squier, and G. Mourou, *Laser-induced breakdown by impact ionization in* SiO_2 *with pulse widths from 7 ns to 150 fs*, **Appl. Phys. Lett. 64**, pp. 3071–3073, 1994.
5. Y. Li, K. Itoh, W. Watanabe, K. Yamada, D. Kuroda, J. Nishii, and Y. Jiang, *Three-dimensional hole drilling of silica glass from the rear surface with femtosecond laser pulses*, **Opt. Lett. 26**, pp. 1912–1914, 2001.
6. T. N. Kim, K. Campbell, A. Groisman, D. Kleinfeld, and C. B. Schaffer, *Femtosecond laser-drilled capillary integrated into a microfluidic device*, **Appl. Phys. Lett. 86**, p. 201106, 2005.
7. S. Lee, E. F. Hasselbrink, and A. J. Hunt, *Nano-acoustic interaction governing high aspect ratio nanochannel femtosecond laser machining*, **Proc. MicroTAS 2006 Conf. 1**, pp. 13–15, Tokyo, 2006.
8. D. J. Hwang, T. Y. Choi, and C. P. Grigoropoulos, *Liquid-assisted femtosecond laser drilling*, **Appl. Phys. A 79**, pp. 605–612, 2004.
9. S. Lee, K. Ke, A. J. Hunt, and E. F. Hasselbrink, *Rapidly prototyped 3D nanofluidics in glass*, **Proc. MicroTAS 2005 Conf. 1**, pp. 524–526, 2005.