Feature Characterization of Microfluidic Channels Created Using Direct Laser Ablation

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Introduction

Microfluidic devices, with their ability to manipulate and analyze nanoliter volumes of chemicals and other fluids, have attracted great interest across a broad range of research and industrial applications. Corporate and academic laboratories around the world are deeply engaged in developing manufacturing technologies for these devices, hoping to create the same kind of benefits and value that accrued from the miniaturization and large scale integration of electronic devices. The flexibility and programmability of direct laser ablation make it attractive as a fabrication technology, but many other aspects of its performance remain to be understood and characterized. Advanced confocal microscopy, which provides fast, high-resolution, three-dimensional visualization and measurement of micrometer scale structure, is ideally suited to this characterization task.

Microfluidic devices are already quite common. For instance, inkjet printers, found in nearly every office and many homes, use micro scale nozzles and heating chambers to precisely project picoliter droplets of ink onto media that range from photo paper to canvas. Current generation photo quality printers generate images that rival, and will likely soon exceed, the quality and resolution of film-based processes.

A whole new generation of microfluidic-based systems is on the horizon. Handheld devices will soon be available for medical analysis of body fluids, detection of hazardous chemicals in the air or soil, or early warning of chemical and biological weapons. They will take analysis out of the lab and into the field, eliminating much of the time and expense now required for laboratory based testing, and empowering medical, military, hazardous materials and other emergency personnel to respond quickly and decisively to their respective challenges.

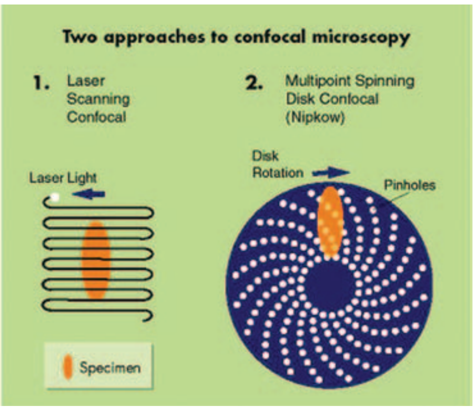
Direct Laser Ablation

Direct laser ablation (DLA) is one of several techniques for producing the microchannels and other micrometer scale structures used in microfluidic devices. It uses a powerful excimer laser to remove material from glass or other substrate materials. DLA combines great flexibility with submicrometer precision to create a wide range of features with carefully controlled sizes and shapes. With programmable control, the system can create complex structures and extensive patterns automatically, with minimal operator interaction, much like a CNC machine tool.

The application of direct laser ablation to microfluidic device manufacturing is relatively new. The continued development of this technique will require a significant amount of experimentation. The effects of beam energy, step size, and exposure time are some of the variables that need to be understood and characterized as the technique matures. Other areas of investigation include surface roughness and the presence or absence of re-deposited material.

Advanced Confocal Microscopy

Advanced Confocal Microscopy (ACM) is a powerful three dimensional visualization technique providing nanometer scale vertical resolution and diffraction limited lateral resolution (about 0.5 micrometers). It is built on a standard optical microscope platform, thus affording the user all the capabilities of a high quality binocular microscope in addition to ACM. Unlike laser scanning confocal microscopes, ACM uses a Nipkow disk, containing an array of apertures and located at the confocal plane, and specially integrated optics to generate the confocal image. Data are collected simultaneously through multiple apertures in the spinning disk to provide significant improvements in data acquisition speed. The use of broad spectrum white light illumination completely eliminates the need for expensive and potentially dangerous lasers. Further microscope modifications provide the precise relative movement between the sample and the object plane used to acquire a sequence of horizontal, confocal images at incrementally different vertical positions through the targeted features. Finally, powerful 3D reconstruction software compiles the stack of digital images into a three dimensional model of the sampled region. The program's intuitive interface allows the user to manipulate the model to make measurements, trace profiles, cut virtual cross sections, change viewing angles, and more. Detailed three dimensional visualization often reveals subtle features not easily seen with standard microscopic inspection techniques.



ACM has several distinct advantages over competing techniques. Unlike profilometers and scanning probes, ACM is a purely optical, non-contact technique, allowing it to be used for process or quality control without risking sample damage. It is fast. The complete acquisition, reconstruction and display process generally takes less than a minute and often less than 30 seconds. ACM places no restrictions on the sample environment. Samples are scanned under ambient laboratory conditions, eliminating

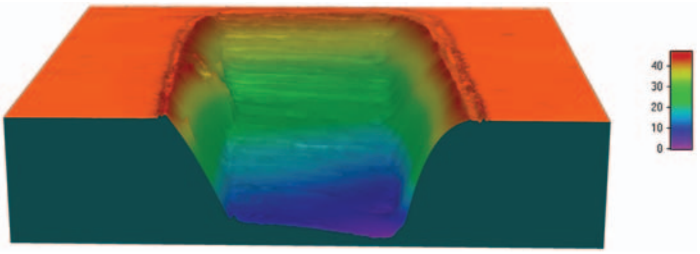
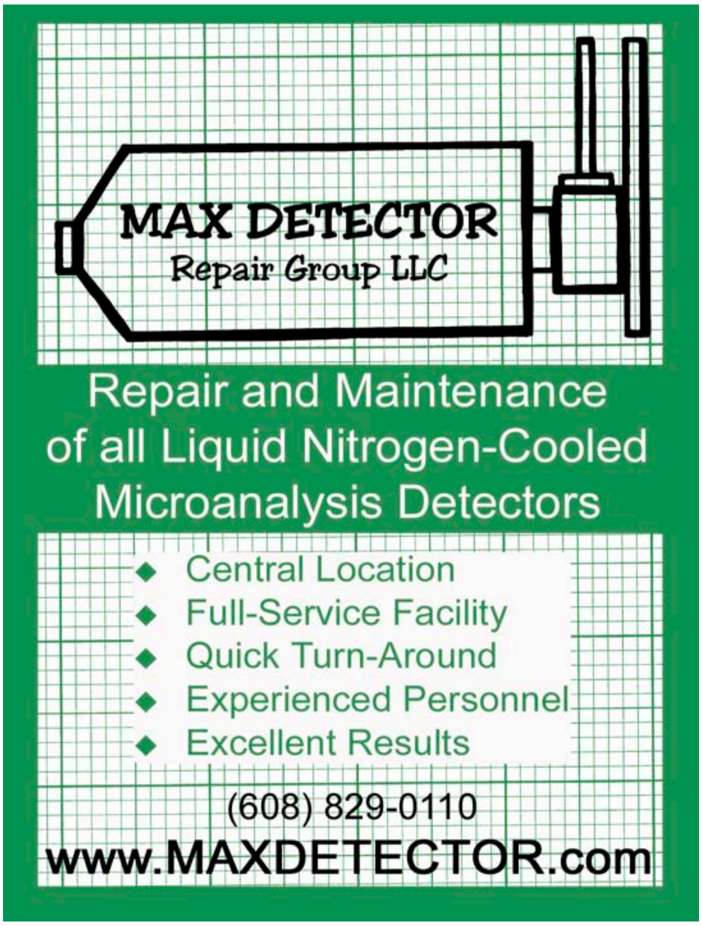


Fig. 1 – 3D Image of microchannel fabricated with laser ablation. The laser was not properly aligned to be perpendicular to the glass resulting in a sloped bottom. This is easily and clearly determined very quickly using Advanced Confocal Microscopy. Channel Width = 95 μm



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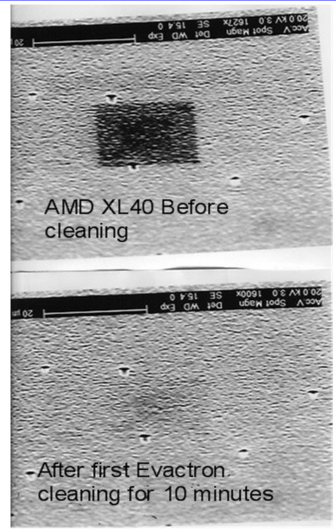

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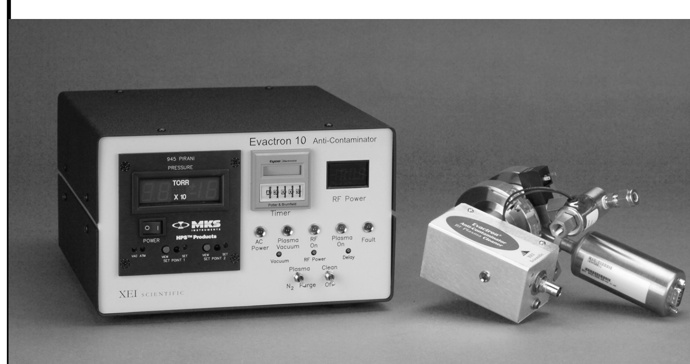

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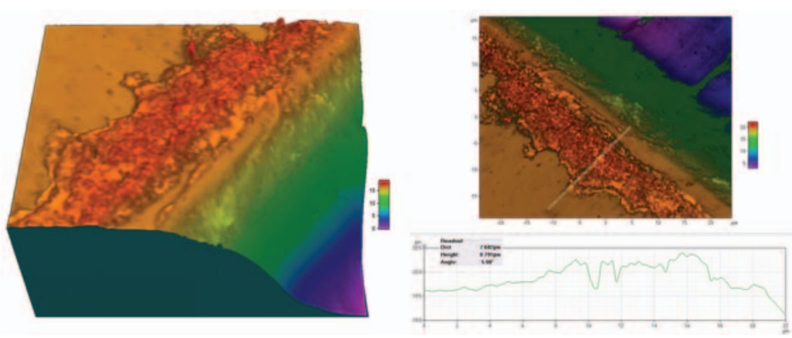

Fig. 2 – The 3D image of the channel edge (left) shows a region on the upper surface where material was re-deposited during the laser ablation process. The 2D metrology mode (right) shows a detailed surface profile, including measurement cursors placed to measure the height of the raised ridge, which is approximately 1 micron in height.

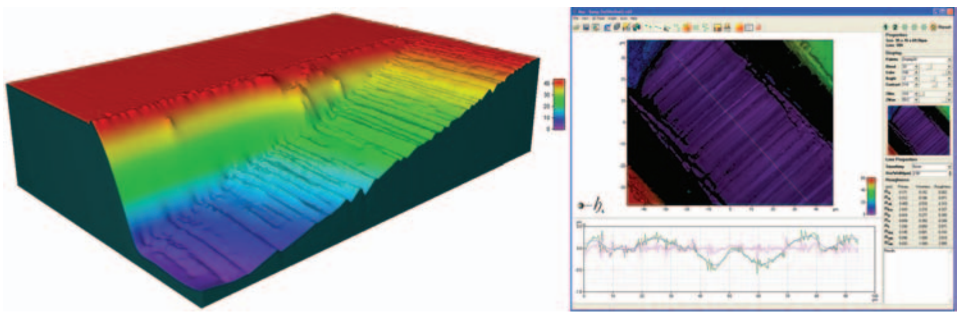

Fig. 3 – The stepping mechanism of the laser creates a lower surface with ridges that resemble a washboard. This feature is easily seen in the 3D image (left) and easily measured using the roughness measurement tool in the metrology mode (right).

many of the elaborate sample preparation required for electron microscopy. Finally, ACM handles rough surfaces, sloped surfaces and subsurface features in transparent materials that are difficult or impossible to observe with interferometric techniques.

Microchannel Feature Characterization

Most new techniques for microfabrication encounter technical challenges along the way, and DLA is no exception. The high Z sensitivity of ACM is well suited to several of DLA's key challenges. With this in mind, the University of Massachusetts Advanced Technology & Manufacturing Center (ATMC, Fall River, MA) and Hyphenated Systems (Burlingame, CA) entered a joint development agreement to assess the capabilities of ACM for characterizing DLA created microchannels.

Laser alignment is a critical parameter in the laser ablation process. If the laser is not perpendicular to the substrate the channel can have a sloped bottom with poor flow characteristics and uneven appearance **(fig 1)**.

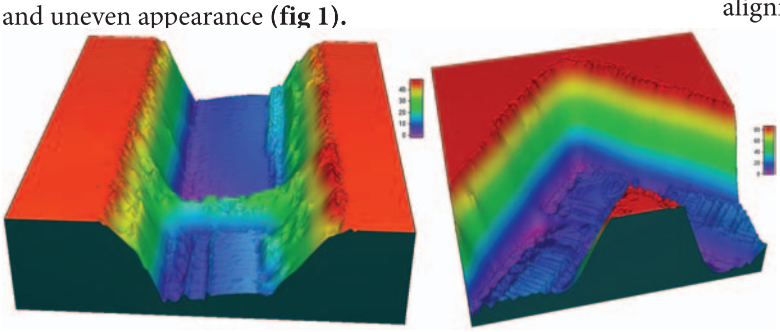

Fig. 4 – The image on the left shows an incomplete laser overlap that left a significant ridge of material perpendicular to the channel. The image on the right shows a corner machined with a laser. The overlap was good and left a fairly smooth channel bottom throughout the corner feature.

Another challenge associated with DLA is the accumulation of a ridge of re-deposited material along the top edges of the channel. This ridge, approximately 1 micron in height, can create difficulties when trying to seal the channel as the rough texture interferes with seal adhesion **(fig 2)**.

The ridge does not always occur. It can be minimized by using the proper combination of laser beam energy, step sizes, and other operating parameters. We have used ACM extensively in our effort to understand and manage the ridge forming mechanism, primarily because of the speed and ease with which it characterizes the channel edge after the laser ablation process.

Ultimately, the purpose of all successfully fabricated microchannels is the transport, mixing, or other manipulation of fluids. Precise control of these fluids requires a detailed understanding of the flow dynamics within the channel. Channel surface characteristics, such as roughness and the presence of ridges or other distinct features, can significantly affect flow in the channel, and ultimately, the operating characteristics of the microfluidic device.

Because a laser essentially steps through its pattern when removing material, the lower channel surface can acquire a ridged surface resembling a washboard **(Fig. 3)**. The physical characteristics of this surface greatly affect the amount of turbulence in a fluid flowing through the channel.

Overlaps and gaps in the laser pattern also create characteristic features. In some cases, such as corners, overlap is difficult to avoid. In other cases there is not enough overlap between lines, leaving a ridge of material behind. **(Fig 4)**. Both cases will affect the flow characteristics of the channel.

Summary

The precise *Z* measurement capability of Advanced Confocal Microscopy provides researchers with the ability to quickly and easily identify microfluidic device fabrication challenges. The ease and speed of imaging gives students and operators virtually immediate feedback on the results of changes in operating parameters such as beam energy, step size, exposure, and beam alignment. Depth control, overlap patterns, and surface features are well resolved and easily evaluated. Because ACM is non-invasive and requires no sample preparation, devices can be reworked and reevaluated repeatedly. ■

All images shown are microchannels in glass created at the UMass ATMC, courtesy of Dr. Lamar Bullock.

Dan Borah is a candidate for a Master of Science degree in Mechanical Engineering at the Advanced Technology and Manufacturing Center, University of Massachusetts, Dartmouth. This work was done under the supervision of thesis advisor Professor Sankha Bhowmick and research supervisor Dr. Lamar Bullock at the ATMC.

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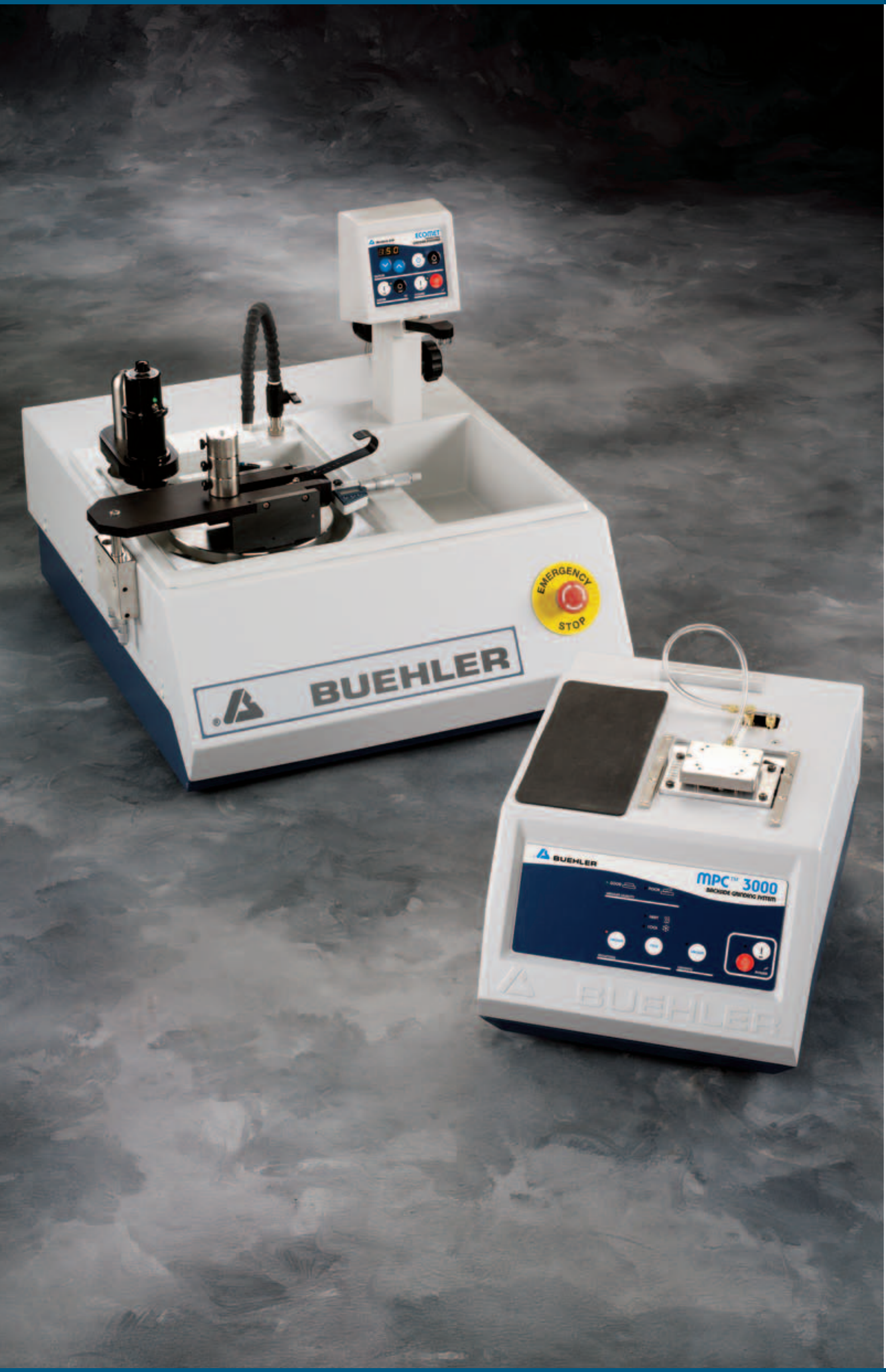

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