ULTRAFAST LASER PULSETRAIN BURST PROCESSING OF GLASSES FOR DAMAGE MITIGATION

by L. McKinney, J. Dean, P. Forrester, M. Nantel and R.S. Marjoribanks

In modern high-intensity laser applications using large-diameter optics, approaching 1 meter in diameter, the lifetime and practicality of the components is affected by concerns of laser damage [1]. Such optics cannot practically be manufactured defect-free, and flaws can be acquired during handling and use. A routine method of repairing and mitigating damage to components such as fused silica lenses and windows is required. One proposal is to mitigate damage by cutting out localized defects using ultrafast laser machining, trimming and 'healing' small damage sites before they can grow and cause further problems during use.

We present the results of processing fused silica with ultrafast-laser pulsetrain-burst processing, and describe the background science, with application to mitigation and repair of high-power laser-damage in optical components.

The mitigation processing must create a crack-free surface without debris or recast, which could lead to further damage. Micromachining using ultrashort laser pulses permits precise etch-control, with negligible accumulated thermal stress compared to longer-pulse methods; this is particularly useful for transparent materials such as glasses. The special advantages of ultrafast-laser material processing have been explored and developed in recent years [2-5].

In this work we report using ultrahigh-repetition-rate (133 MHz) laser pulsetrain-bursts of 1–15 μs, energies up to 20 mJ per shot, and individual-pulse durations of 1–10 ps, to process optical materials with an aim of avoiding or mitigating damage caused by nanosecond high-energy laser pulses. We have characterized the morphology of machining by ultrafast pulsetrain-bursts in fused silica and identified how to control machined surface features and surface smoothness.

The mix of timescales (pulse-duration and pulse-separation) involved in pulsetrain-burst processing gives new dimensions of control of the fluence delivered to the target. The ultrashort pulses have the advantages of material ablation with minimal direct coupling of laser energy into the solid material lattice [6-8]. The 7.5 ns pulse separation allows us to take advantage of plasma persistence and cumulative heat deposition effects, where the processing proceeds on a material that the pulsetrain itself has modified. For instance, making brittle glass progressively more ductile during machining by a long train of pulses at near-threshold intensity, results in a smooth hole with no cracking, (Fig. 1).

The laser used in these experiments is a flashlamp-pumped picosecond Nd:glass system (λ = 1054 nm) purpose-built at the University of Toronto [9]. An oscillator with active/passive and feedback-controlled modelocking produces a quasi-cw pulsetrain of over 3000 pulses, with pulse duration adjustable in the range 950 fs–10 ps.

Individual pulses from the oscillator have energies up to 1 μJ, with inter-pulse separations of 7.5 ns. A Pockels cell N-pulse slicer selects a square burst of pulses from the train, 0.5–10 μs long, for further amplification. Two multi-pass Nd:glass amplifiers increase the per pulse energy to up to ~ 10 μJ per pulse, giving a total train energy of up to 20 mJ in a 15 μs burst.

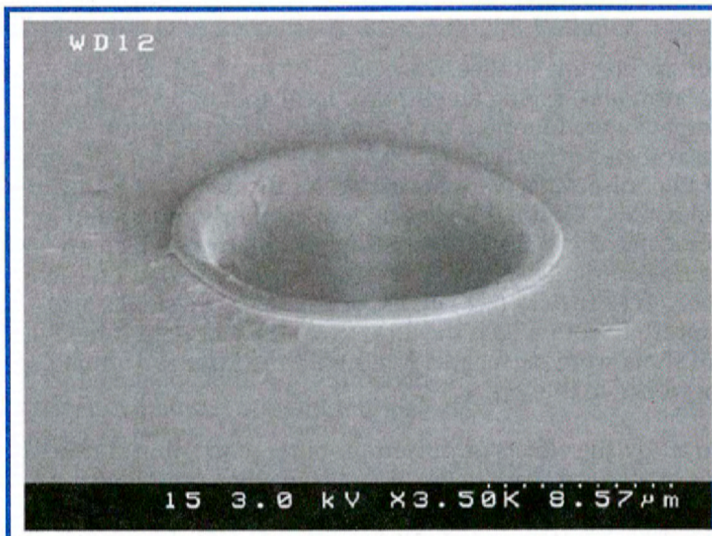

Fig. 1 SEM image of a smooth, crack-free feature over 30 μm deep drilled in fused silica by a single pulse-train burst of 430 x 1.2 ps pulses.

L. McKinney [a], J. Dean [a], P. Forrester [a], M. Nantel [a,b], R.S. Marjoribanks [a], [a] University of Toronto, Department of Physics and Institute for Optical Sciences, 60 St George St., Toronto, M5S 1A7; [b] Ontario Centres of Excellence Inc., 2655 North Sheridan Way, Mississauga, Ontario L5K 2P8

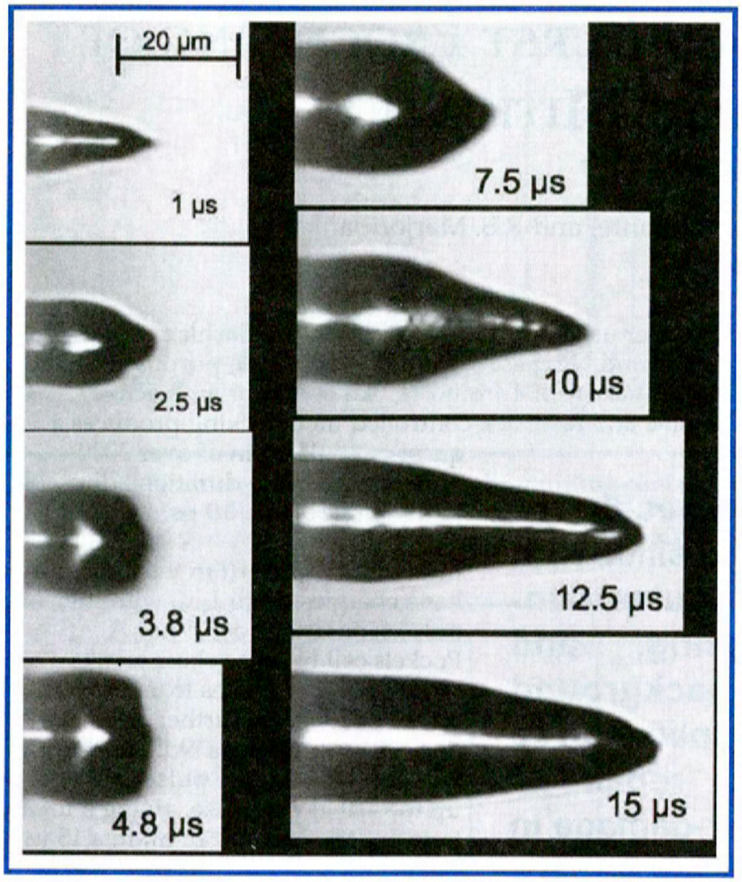

Fig. 2 Profiles of features drilled by pulsetrain-bursts of varying length, delivering a fluence of 6.9 ± 1.7 J/mm^2 per microsecond.

For the current studies, the beam was focussed using a 13.8mm lens, giving an elliptical focal spot of 5 x 7 µm. Targets were mounted on an *xyz* translation stage of micrometer precision. Temporal profiles and total energies of the pulsetrains were measured for incident and transmitted beams. Optimal focussing was regularly monitored by autocollimating the retro-reflected beam, from which an equivalent-target-plane (ETP) image was recorded on each shot. A near field (NF) image of the beam waist was also captured, from which the focal spot size was determined. All shots were performed in air with the laser at normal incidence to the target.

To study the effects of pulsetrain-burst machining, a number of features were drilled in a fused silica sample using pulsetrains of varying length and constant average fluence of 6.9 ± 1.7 J/mm^2 per microsecond. Figure 2 shows optical microscope images of features drilled in fused silica, with the laser incident from the left. The white lines and blobs visible are simply reflections of the optical-microscope light source from the smooth walls of the feature. In figures 2 and 3 we see a clear bimodal evolution in shape, with a distinct widening stage (from 1 to 5 µs) where the hole expands barrel-like without deeper drilling once a depth of ~ 20 µm is reached, followed by deeper drilling once a certain width has been reached.

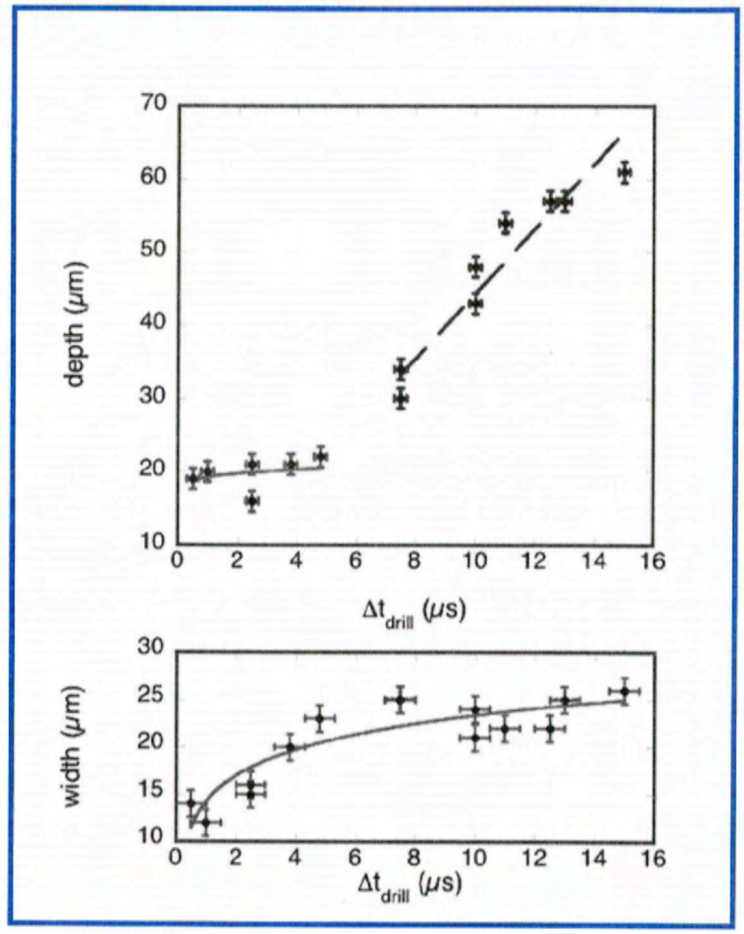

Fig. 3 Depth (top) and surface-width (bottom) trends of the features drilled with varying pulsetrain burst length, delivering a constant average fluence of F = 6.9 ± 1.7 J/mm^2 per microsecond.

This can be understood in terms of a plasma-mediated ablation process. Once a laser causes optical breakdown in the material a plasma is produced. This plasma does not disperse completely in the 7.5 ns between our laser pulses, and subsequent pulses find themselves incident on an underdense plasma but can still penetrate to the base of the hole and continue ablation. As the channel becomes deeper, the plasma cannot disperse as effectively, until at a certain depth a critical-density plasma persists between shots and completely absorbs incident laser pulses. Ablation then proceeds by a plasma-mediated process, widening the feature as it burns in all directions, fed by incident laser energy. This produces the distinct shapes such as those for 3.8 and 4.8 µs pulsetrains in Fig. 1, with concave walls and wider cavities deeper in the bulk rather than near the surface. Once the now-barrel-like hole becomes wide enough, the plasma can disperse out of the path of the laser effectively and deeper drilling can proceed (at this point the feature is ~ 20 µm wide, while the incident laser beam focal spot is ~6 µm across).

Numerical simulations were performed using the one-dimensional lagrangian hydrocode MEDUSA [10,11] to sketch the behaviour of the reflection point in this propagation, at

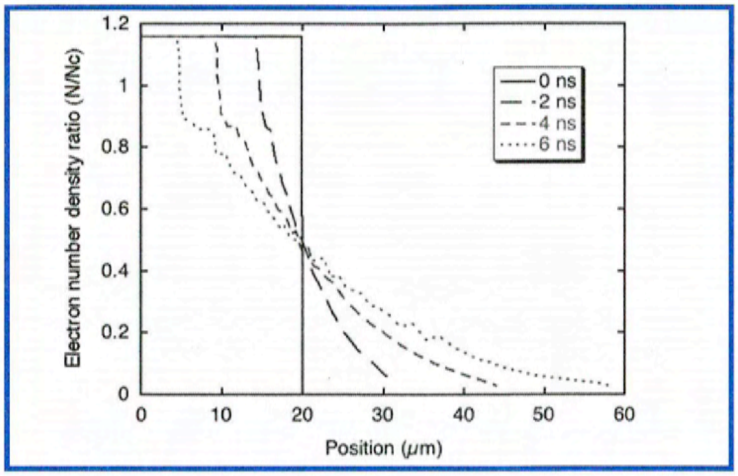

Fig. 4 MEDUSA modeling of plasma expansion, showing density profiles at varying times. A block of constant density plasma at around 1.2 Nc is allowed to expand from time 0 ns. As the plasma expands to the right, a rarefaction front moves into the critical density bulk toward the left.

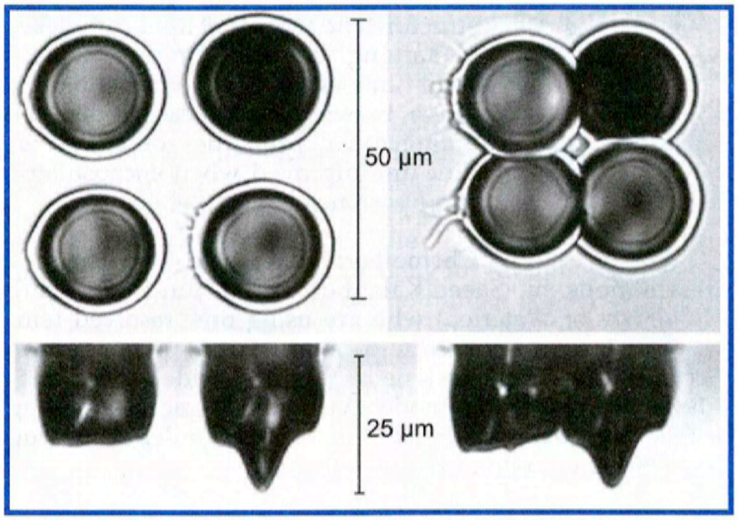

Fig. 5 Surface views (top) and profiles (bottom) of closely written flat bottomed features produced by 3 μs pulsetrains, total energy ~ 2 mJ per pulsetrain. Note that the bright finish on the base of the holes is simply a reflection of the optical microscope light source from a smooth surface.

the critical-density surface. The velocity of the rarefaction front moving through a plasma initially at about 20% over critical density for λ = 1054 nm light was found to be ~ 2,500 m/s for an initially uniform plasma at a temperature of about 1 eV, (Fig. 4). Such a plasma will erode by about 20 μm in the 7.5 ns between pulses, and so subsequent pulses can be expected to propagate inward; this depends, of course, on the details of the plasma formed within the channel. At this critical-density-surface depth, the plasma entirely the absorbs or reflects the incident laser light and the widening stage begins.

With an understanding of the process by which these features are produced, we can then control the features that are produced. By adjusting the length of the pulsetrain so that it ends just as the first widening stage is completed, we were able to produce flat-bottomed cylindrical holes, figure 5. These features are expected to be useful in the goal of damage mitigation, with the ability to neatly scoop out damaged material and leave behind a smooth, well-behaved feature. In Fig. 5 we also see that the features can be produced free from any cracking, recast or debris, as well as being closely spaced or even partially overwritten to form larger features with no adverse effects.

In conclusion, we have examined the effects of ultrafast-laser pulsetrain-bursts as a mode of fluence delivery in the processing of fused silica samples. Smooth, crack-free well-behaved features can be produced repeatably, taking advantage of the ability to machine normally brittle materials. A model explaining feature formation in terms of plasma-mediated ablation is proposed and used. Future work will include finding the damage thresholds of these microprocessed features, and comparing that to the damage thresholds of undamaged material and material suffering from high-power laser-damage.

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