Preprint
UCRL-CR-145536

Comparison of Machining with Long-Pulse Green and Ultrashort Pulse Lasers

A. E. Wynne, and B. C. Stuart

May 18, 2001

U.S. Department of Energy

Lawrence Livermore National Laboratory

Comparison of Machining with Long-Pulse Green and Ultrashort Pulse Lasers

Alexis E. Wynne and Brent C. Stuart
Lawrence Livermore National Laboratory

Contract number L8951
May 18, 2001

Table of Contents 2

Statement of Work

I) LLNL measured the material removal rate from stainless steel, silicon carbide, rhenium, N5, hastalloy X, and titanium as a function of pulse fluence at a wavelength of 810 nm for pulse durations of 150 fs, 1.5 ps, 20 ps, and 500 ps. The spot size of the beam used was 150 microns in diameter and the nominal material thickness was 1-2 mm. These experiments were performed on the existing 1 kHz laser system. Holes of different penetration depths were obtained to ascertain change in removal rate as a function of depth.
Measurements included electron microscopy of selected samples

II) The experiments in I were repeated for all materials but select pulse durations with the sample in a vacuum of base pressure 10 mTorr to determine if hole quality and ablation rate is improved.

III) LLNL measured material removal rate from stainless steel, silicon carbide, rhenium, N5, hastalloy X, and titanium as a function of pulse fluence at a wavelength of 532 nm for pulse duration at 200 ns. The spot size of the beam used was 200 microns in diameter and the material thickness was the same as in task I. Holes of different penetration depths were obtained to ascertain changes in removal rate as a function of depth.

Experimental Set-Up

For the first set of experiments, we used a chirped-pulse amplification (CPA) Ti:sapphire laser and regenerative amplifier system. The system delivered pulses at a repetition rate of 1 kHz with energies up to 1.5 mJ at a wavelength of 810 nm. Because of the CPA configuration, the pulse width could be varied from 150 fs to 20 ps without changing any other parameters. When a 500 ps pulse was needed, the uncompressed pulse was picked off and sent to the drilling chamber.

We used a lens with a focal length of 34 cm to focus the gaussian beam to a round spot. The part was placed before the beam focus in order to achieve a spot size of 150 micron diameter. We used circular polarization to avoid the uneven drilling effects of static linear polarization. The beam hit the part at normal incidence, and the fluence was changed by adjusting the energy while the spot size remained constant.

The materials used were 304 stainless steel, rhenium, titanium, silicon carbide, hastalloy X, and N5. These coupons were placed in a vacuum chamber that has a system of gas baffles that prevent coating the entrance window with the plasma. Argon was bled in at the baffles while the vacuum pump was on to achieve equilibrium. When drilling in vacuum, the pressure in the chamber was 10 mTorr and the pressure at the entrance window was 400 mTorr. When drilled in air, the chamber was vented and the lid left off.

A fast mechanical shutter (UniBlitz) was used to select a defined number of pulses. For each fluence and pulse-width chosen, ten holes were drilled, two holes for each of five different time intervals (number of pulses). The times and corresponding number of pulses chosen varied with fluence to achieve similar depths at all fluences. The depths of the two holes for each number of pulses were averaged in each case and used to determine the drilling rate for that number of pulses. For breakthrough detection, an imaging set-up was installed at the rear end of the chamber. A lens imaged the plane of the part onto a CCD. Breakthrough was timed by first detection of light on the camera after the shutter was opened.

For the second set of experiments, a diode pumped, intra-cavity doubled, Ndd:YAG laser was used. This system delivers 200 ns pulses at a repetition rate of 2 kHz with energies up to 10 mJ at a wavelength of 532 nm. A 15 cm focal length lens was used to focus the gaussian beam to a round spot with a diameter of 200 microns. The part was placed at focus to achieve the smallest possible spot size. The fluence was adjusted by changing the power while the spot size remained constant. The beam hit the part at normal incidence and all holes were drilled in air. The drilling technique was similar to above except that only 6 different fluences were used.

All holes were measured with a Nikon measuring microscope (MM-40) with an encoded Z stage that is connected to a digital read-out (Quadra-Chek 2000). Depths were measured by focusing at the surface of the part, zeroing the read-out, and the focusing at the bottom of the deepest part of the hole. We estimated the error in depth to be +- 3 microns. The fluence was determined by measuring the pulse energy with a Coherent

LM3 power meter and measuring the spot size with Coherent Beam Analyzer software. The error in fluence is determined to be 20% due to laser energy fluctuations and beam diameter measurement error.

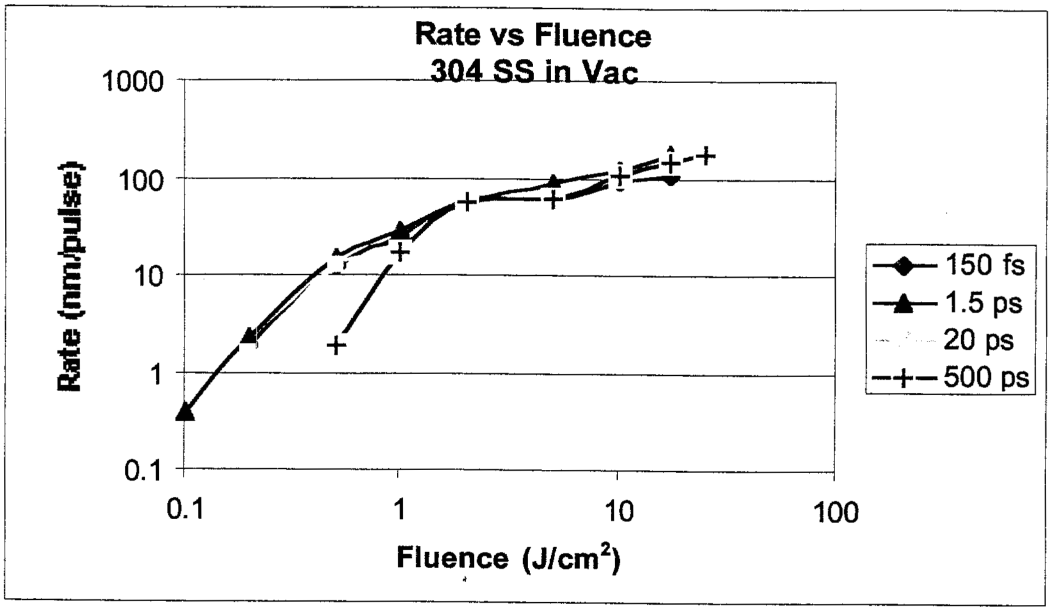
Measurements

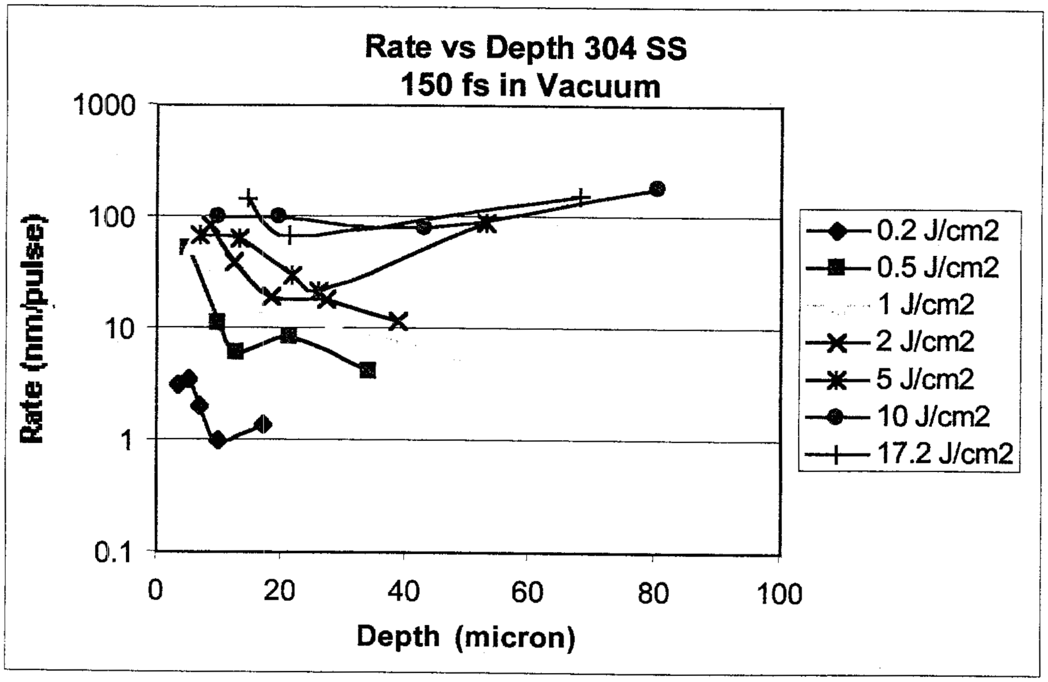
We measured initial ablation rate of all materials as a function of fluence, pulse duration and ambient pressure (air vs. vacuum). In order to calculate the rate curves, a constant depth was chosen for all fluences, and the rate for that depth was plotted against fluence. The depth chosen was between 10 and 20 micron because we noticed that the rate changes dramatically with depth as discussed below.

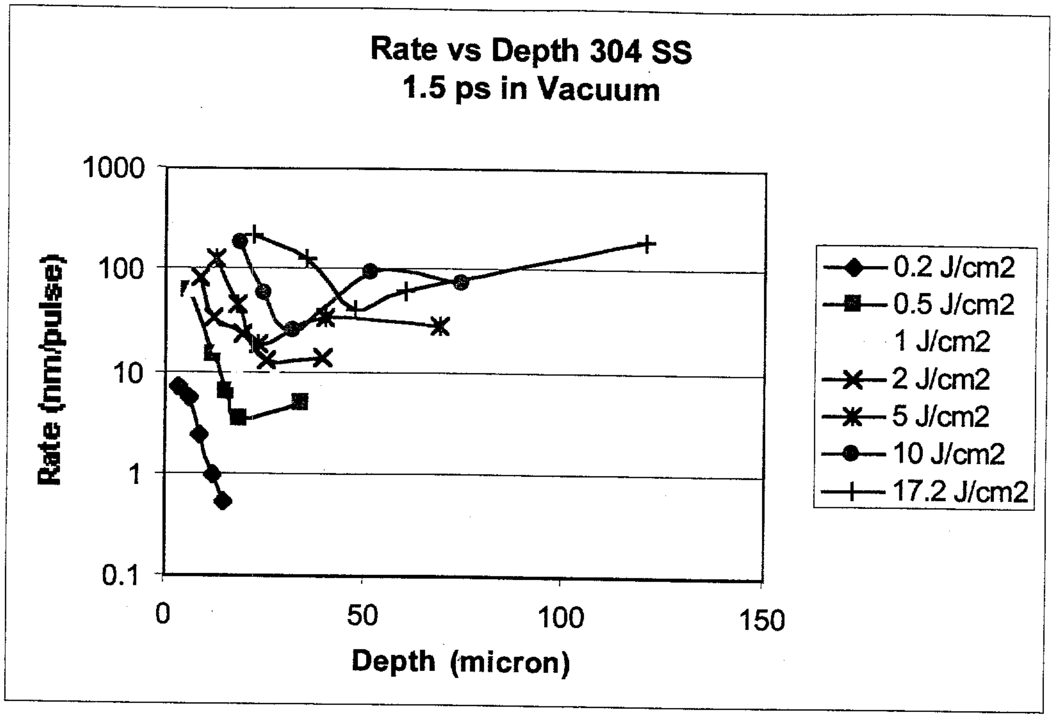
We measured ablation rate as a function of depth for the 810 nm cases in order to better understand how the hole progresses. We also measured breakthrough times for given samples of the materials in order to study completion of high aspect ratio holes.

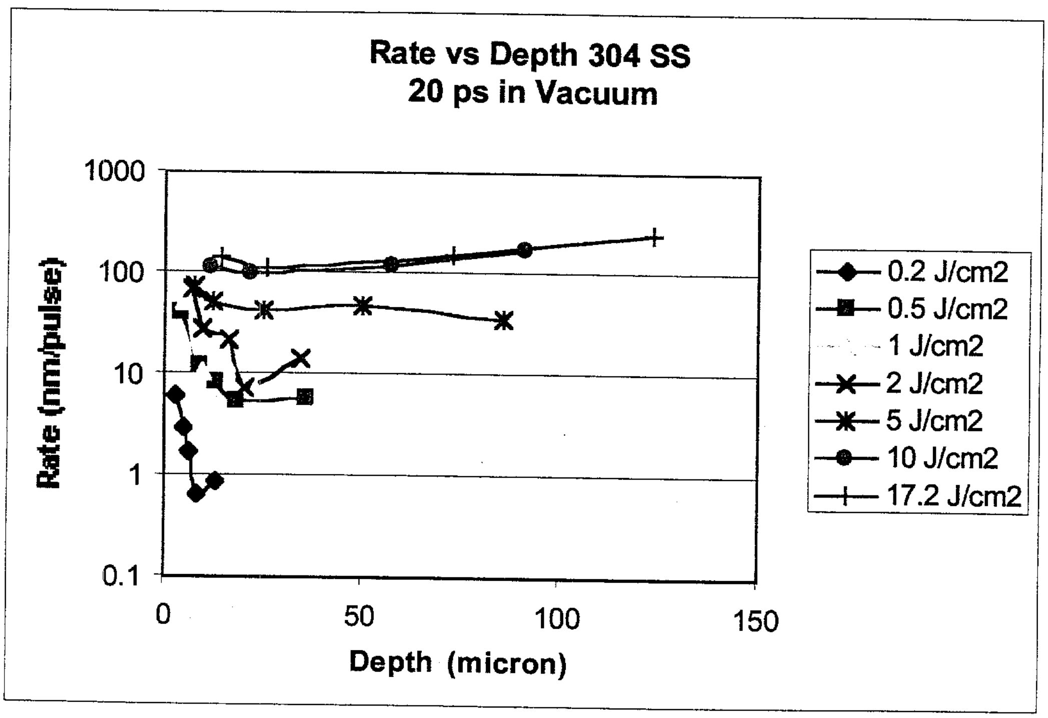
The following data is presented in graphs organized by material. For each material, there are initial ablation rate vs. fluence plots for 810 nm in air and vacuum, as well as green machining. Following that are rate vs. depth curves for select cases using the 810 nm laser. And finally there is a breakthrough time vs. fluence curve for all pulse-widths tested using the 810 nm laser in vacuum and air.

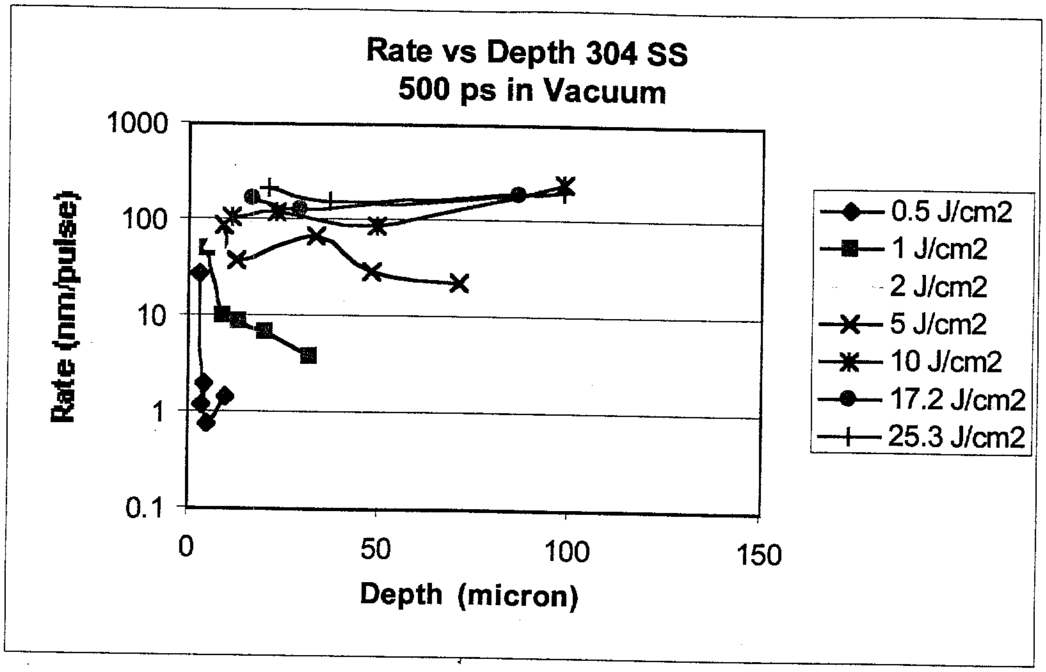
Stainless Steel



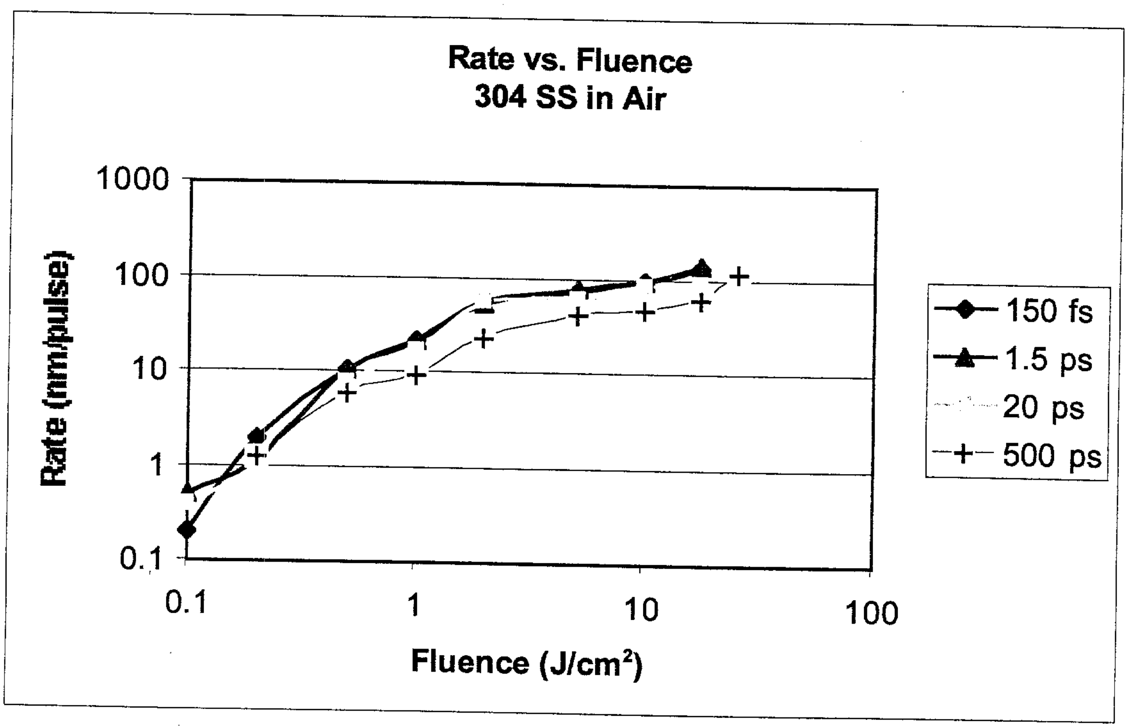



Rate vs Depth 304 SS
1.5 ps in Vacuum
1000
100
10
1
0.1
Rate (nm/pulse)
0
50
100
150
Depth (micron)
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.2 J/cm2

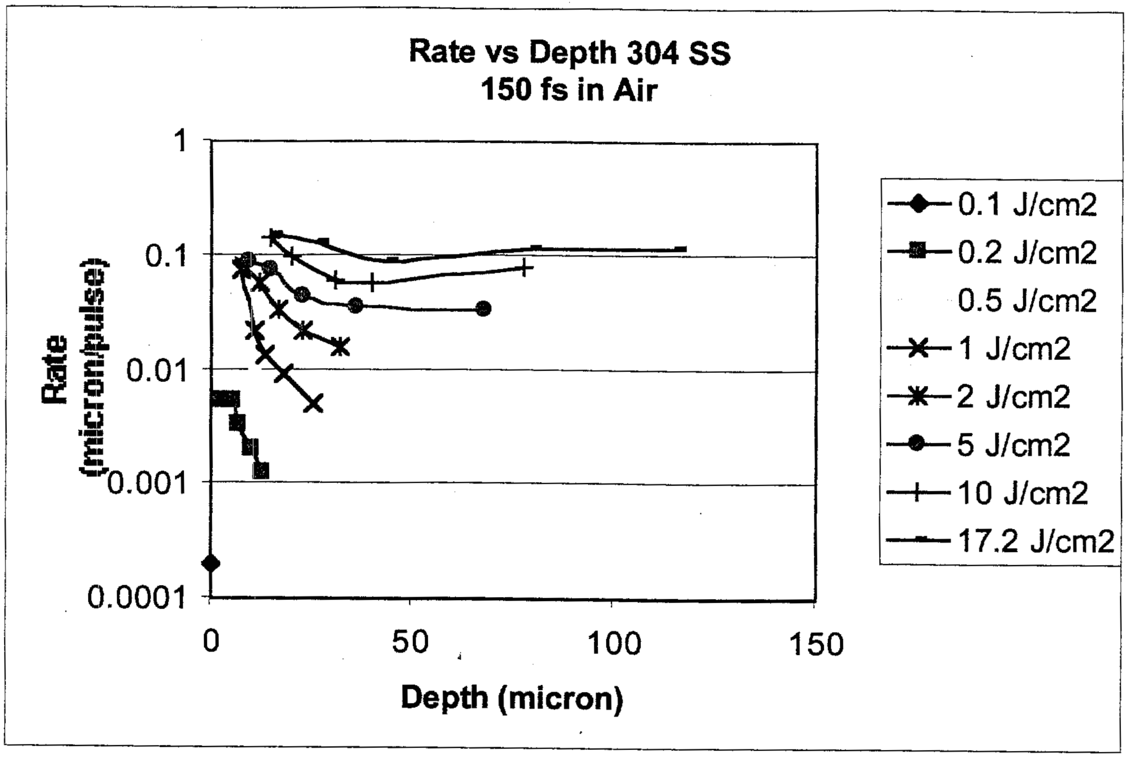

Rate vs Depth 304 SS
20 ps in Vacuum
1000
100
10
1
0.1
Rate (nm/pulse)
0
50
100
150
Depth (micron)
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.2 J/cm2

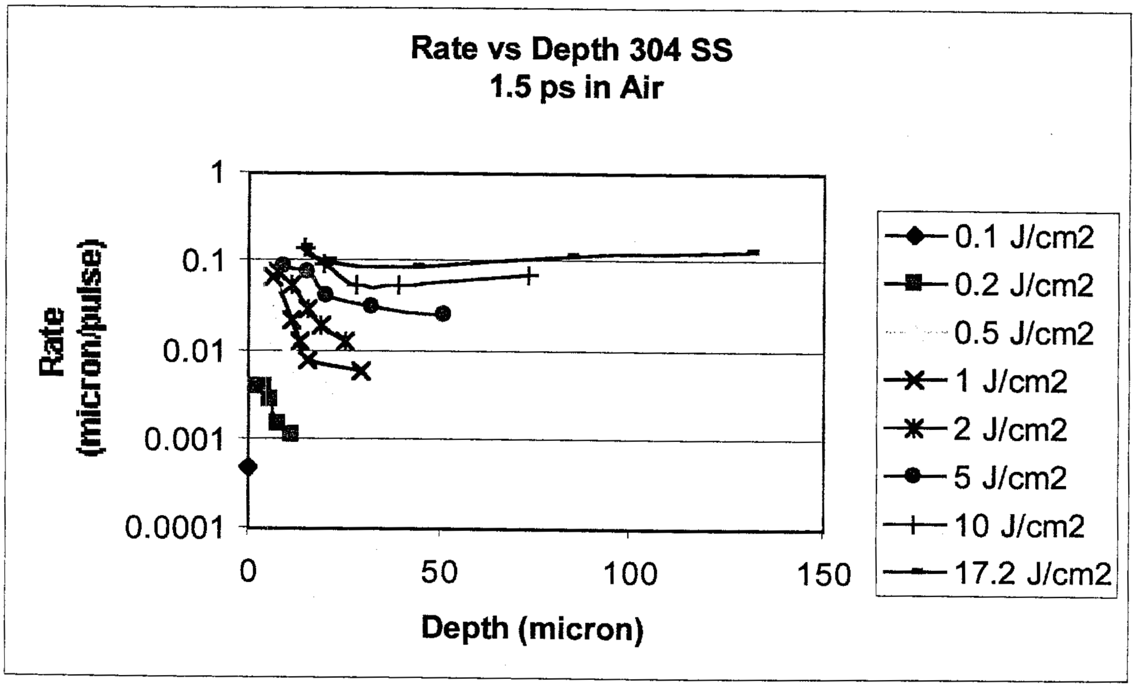


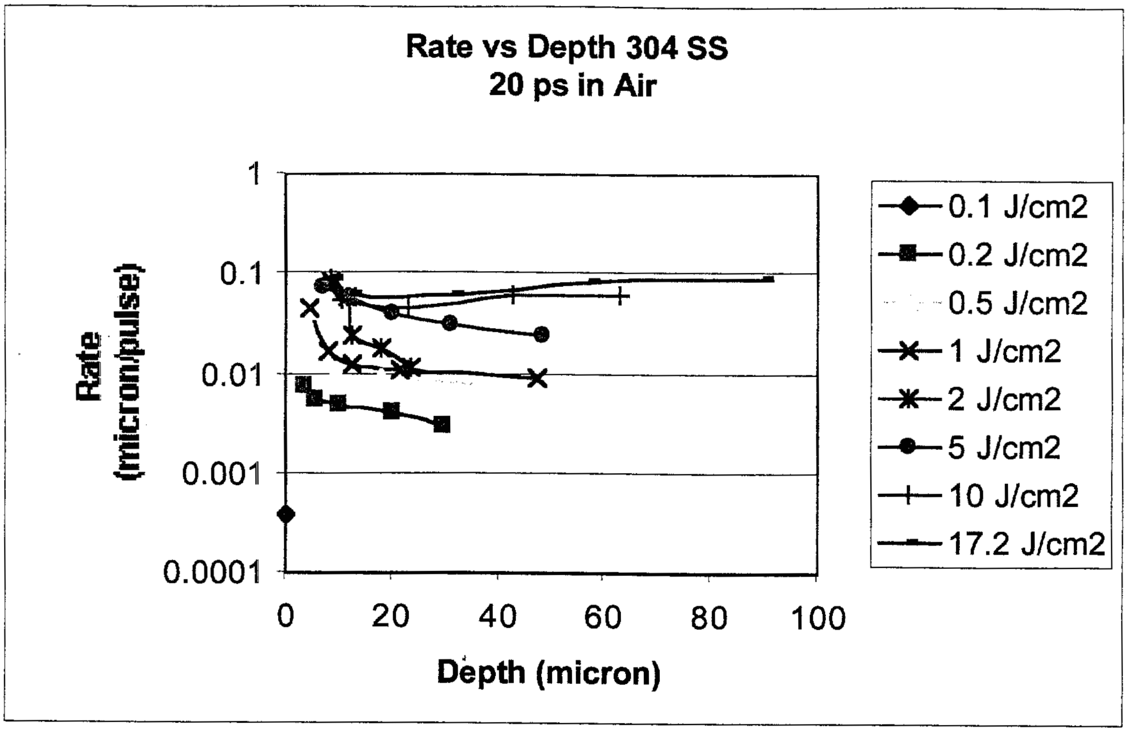
Rate vs Depth 304 SS
500 ps in Vacuum
Rate (nm/pulse)
1000
100
10
1
0.1
0
50
100
150
Depth (micron)
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.2 J/cm2
25.3 J/cm2

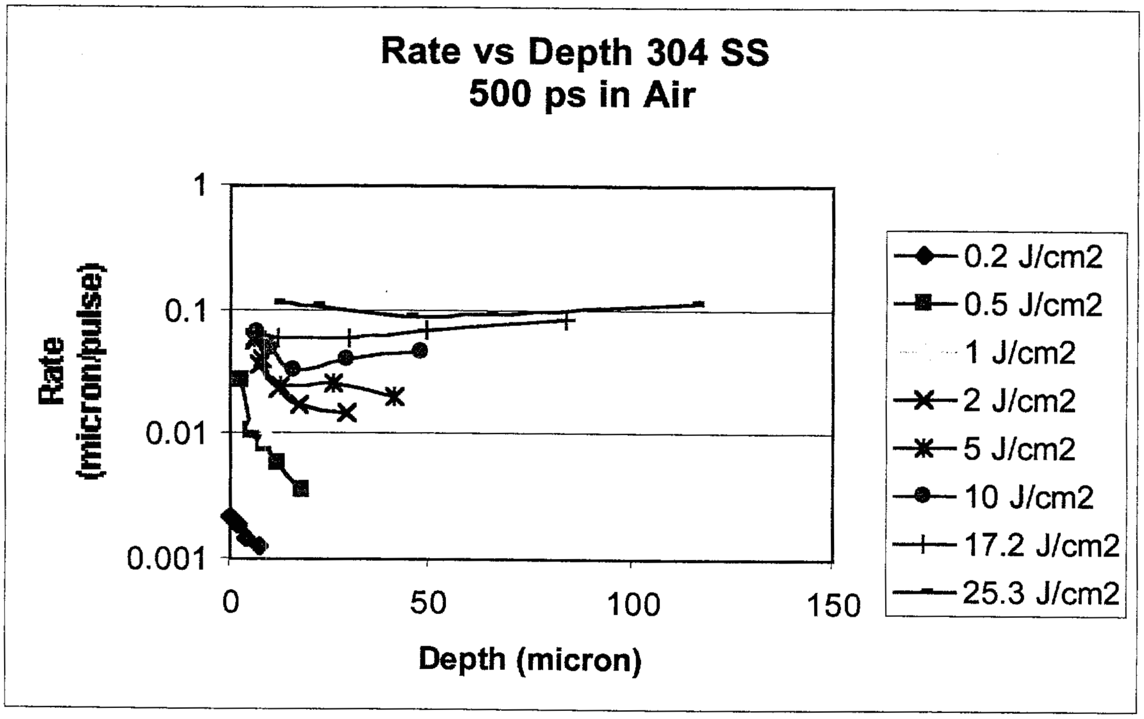


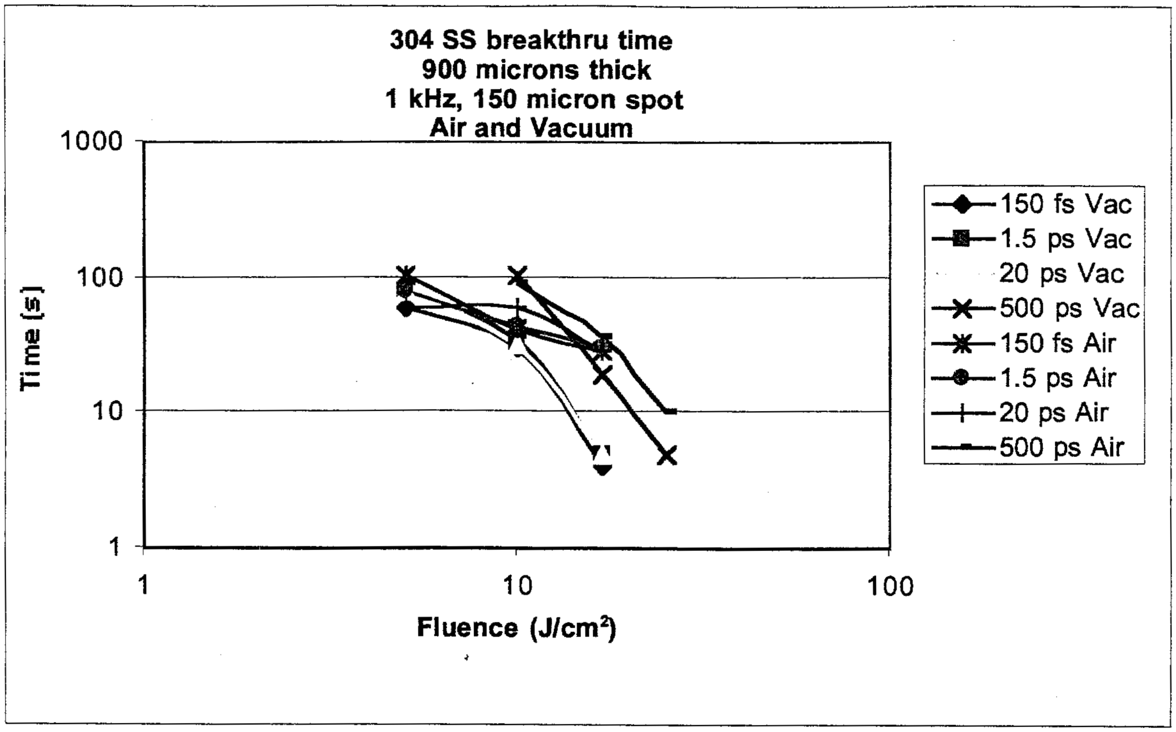
Rate vs. Fluence
304 SS in Air
Rate (nm/pulse)
1000
100
10
1
0.1
0.1
1
10
100
Fluence (J/cm²)
150 fs
1.5 ps
20 ps
500 ps

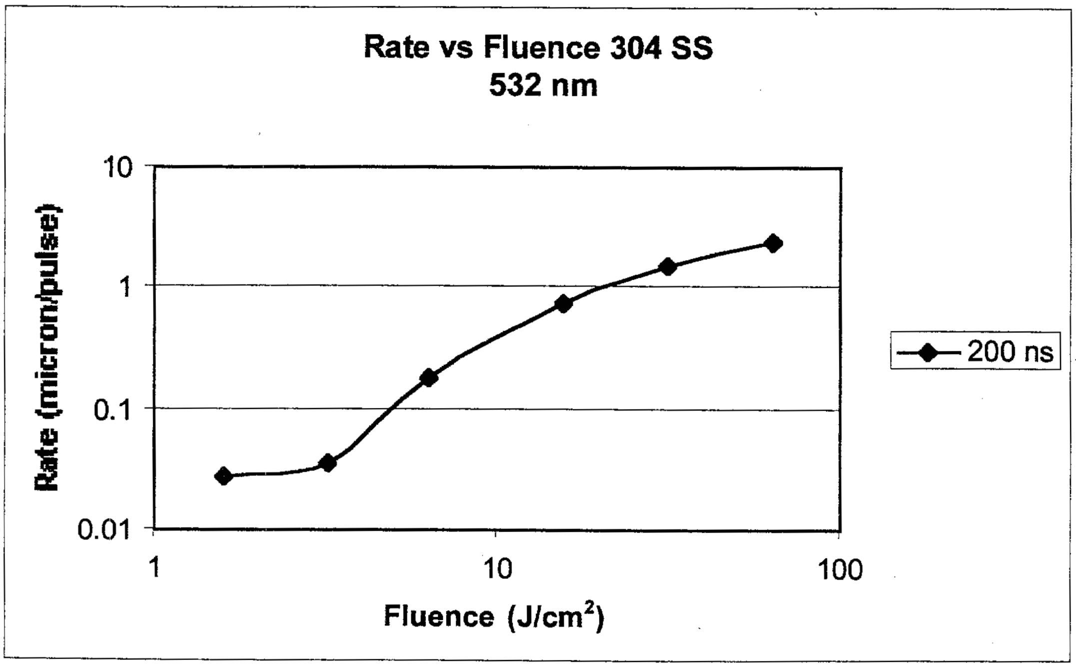

Rate vs Depth 304 SS
150 fs in Air
1
0.1
0.01
0.001
0.0001
Rate
(micron/pulse)
0
50
100
150
Depth (micron)
0.1 J/cm2
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.2 J/cm2


Rate vs Depth 304 SS
1.5 ps in Air
1
0.1
0.01
0.001
0.0001
Rate
(micron/pulse)
0
50
100
150
Depth (micron)
0.1 J/cm2
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.2 J/cm2

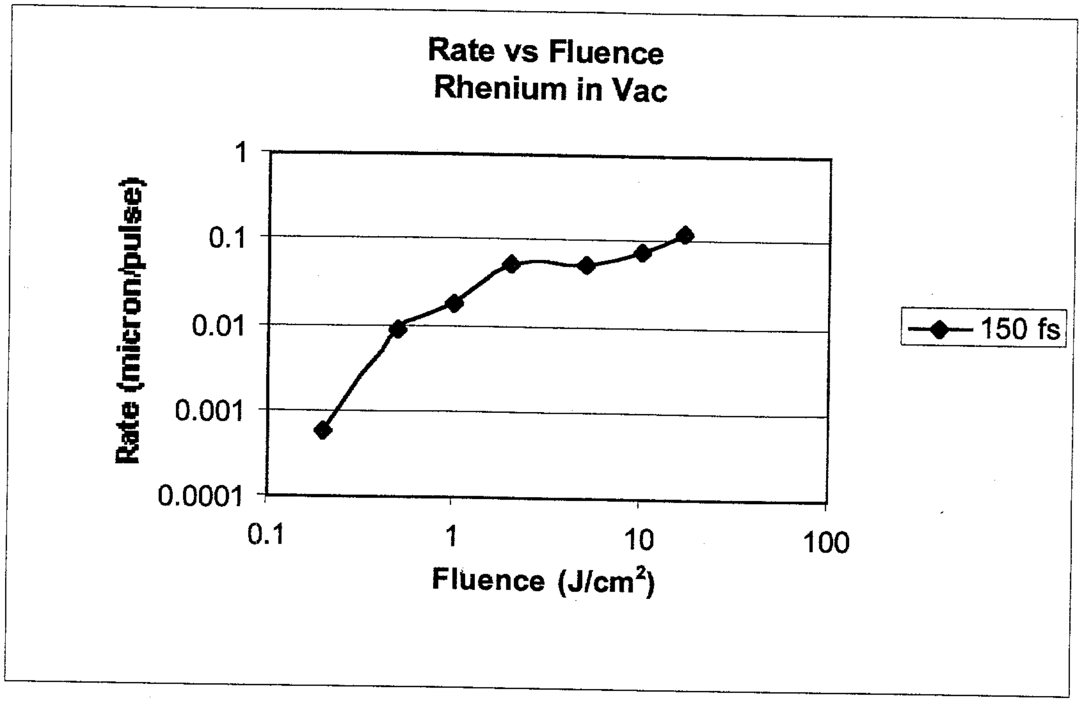

Rate vs Depth 304 SS
20 ps in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0.0001
0
20
40
60
80
100
Depth (micron)
0.1 J/cm2
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.2 J/cm2

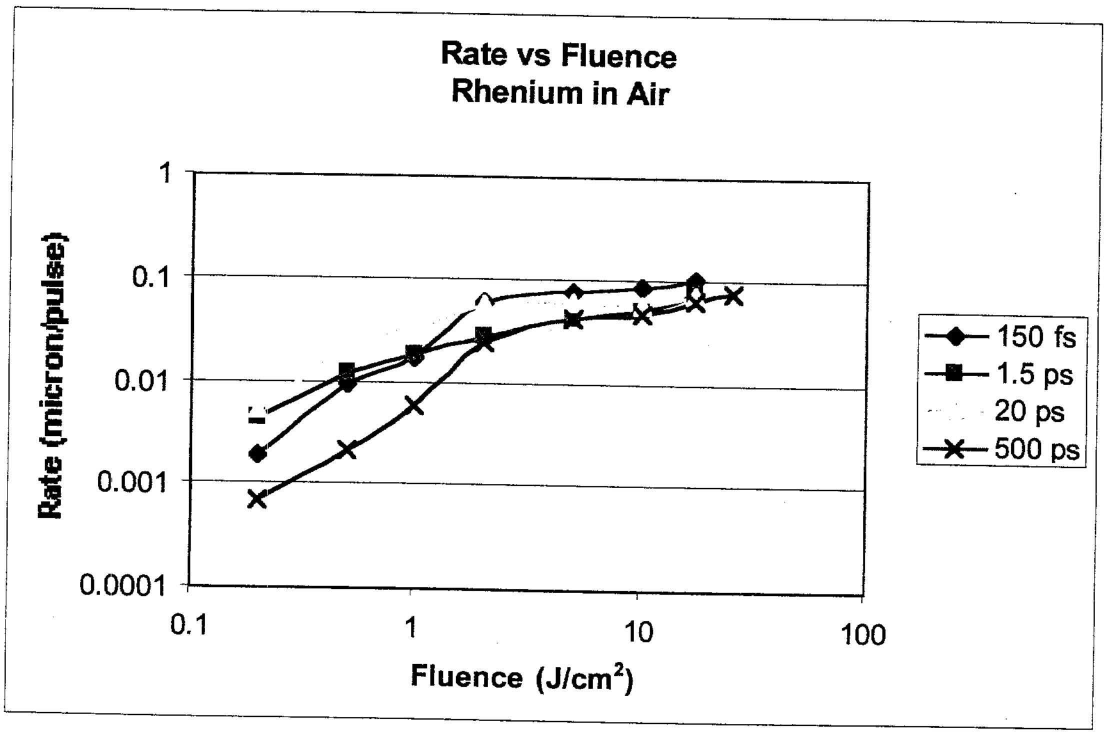

Rate vs Depth 304 SS
500 ps in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0
50
100
150
Depth (micron)
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.2 J/cm2
25.3 J/cm2

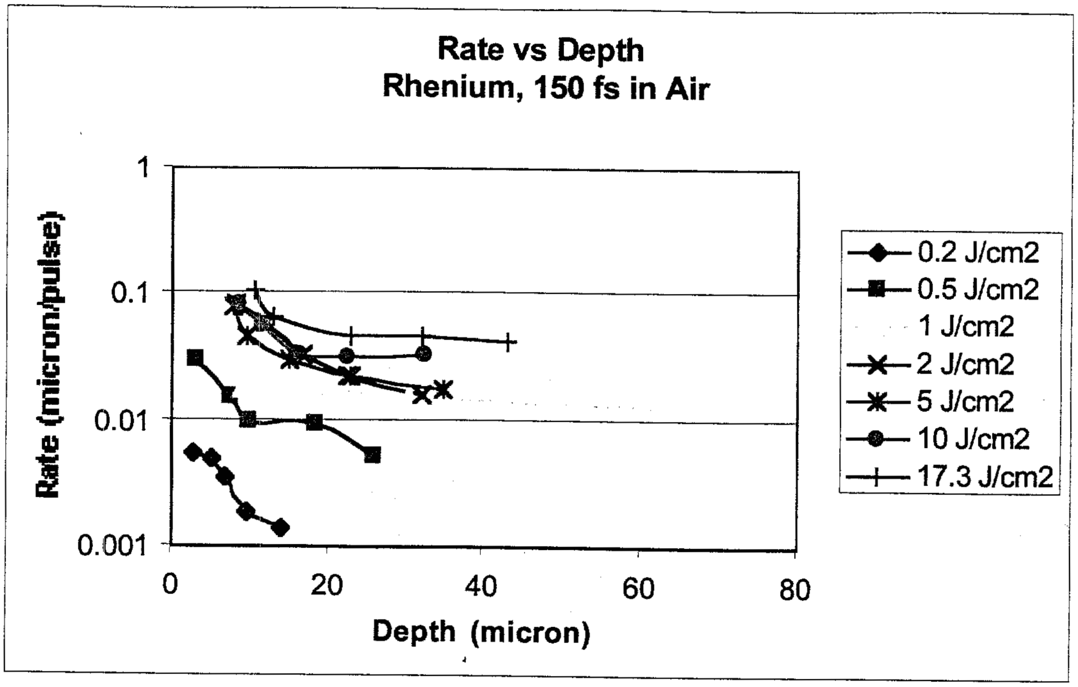

304 SS breakthru time
900 microns thick
1 kHz, 150 micron spot
Air and Vacuum
Time (s)
1000
100
10
1
1
10
100
Fluence (J/cm²)
150 fs Vac
1.5 ps Vac
20 ps Vac
500 ps Vac
150 fs Air
1.5 ps Air
20 ps Air
500 ps Air

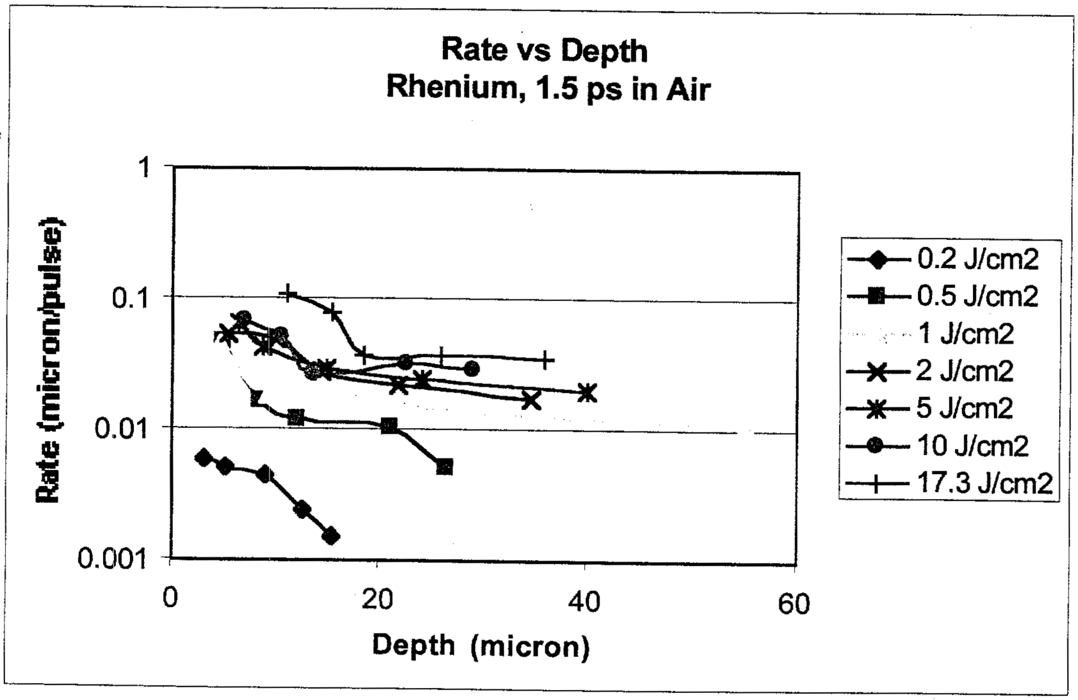

Rate vs Fluence 304 SS
532 nm
Rate (micron/pulse)
10
1
0.1
0.01
1
10
100
Fluence (J/cm²)
200 ns

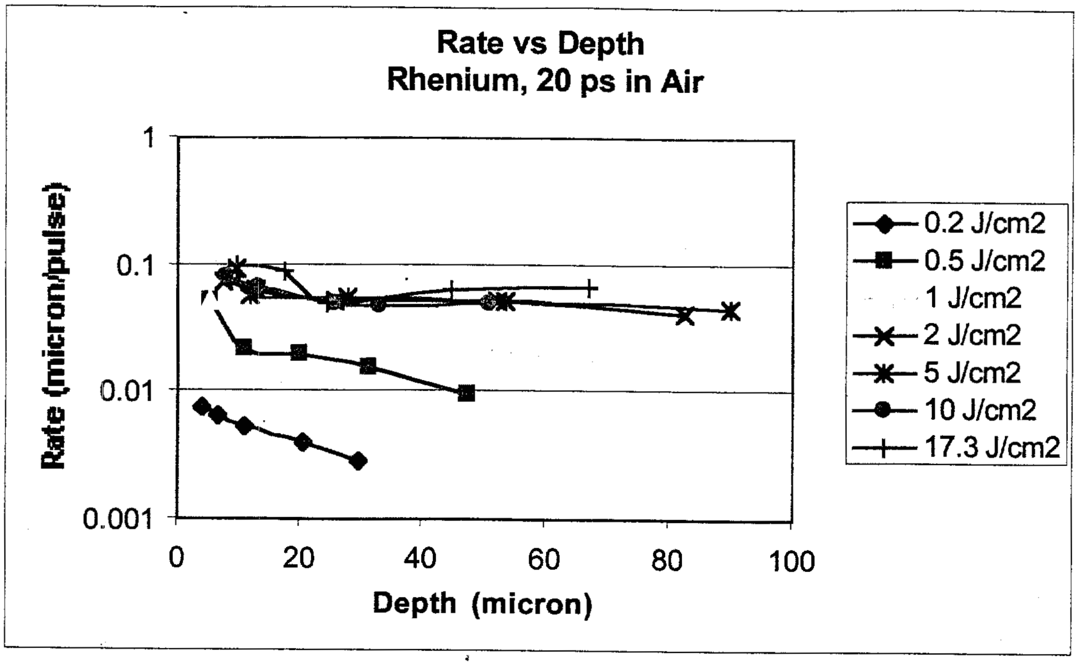
Rhenium

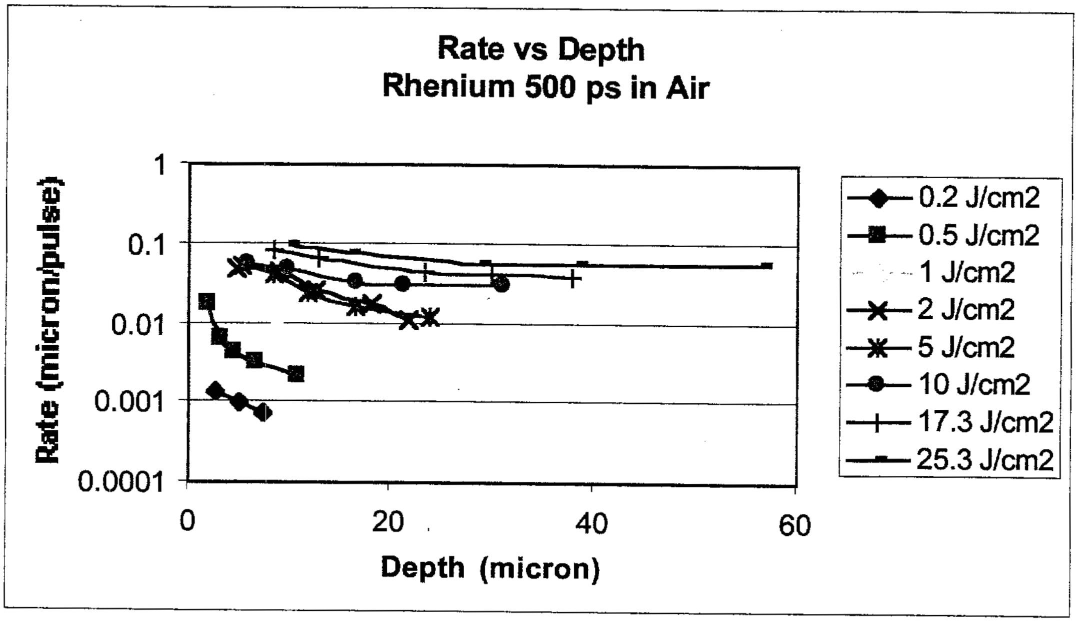

Rate vs Fluence
Rhenium in Vac
Rate (micron/pulse)
1
0.1
0.01
0.001
0.0001
0.1
1
10
100
Fluence (J/cm²)
150 fs

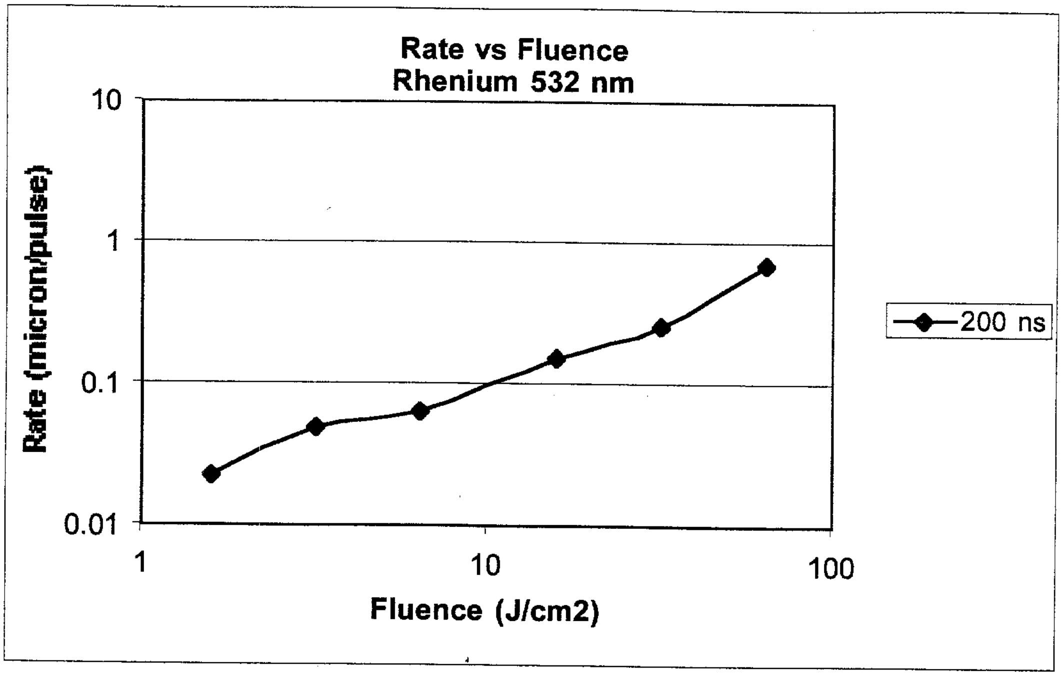

Rate vs Fluence
Rhenium in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0.0001
0.1
1
10
100
Fluence (J/cm²)
150 fs
1.5 ps
20 ps
500 ps


Rate vs Depth
Rhenium, 150 fs in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0
20
40
60
80
Depth (micron)
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.3 J/cm2

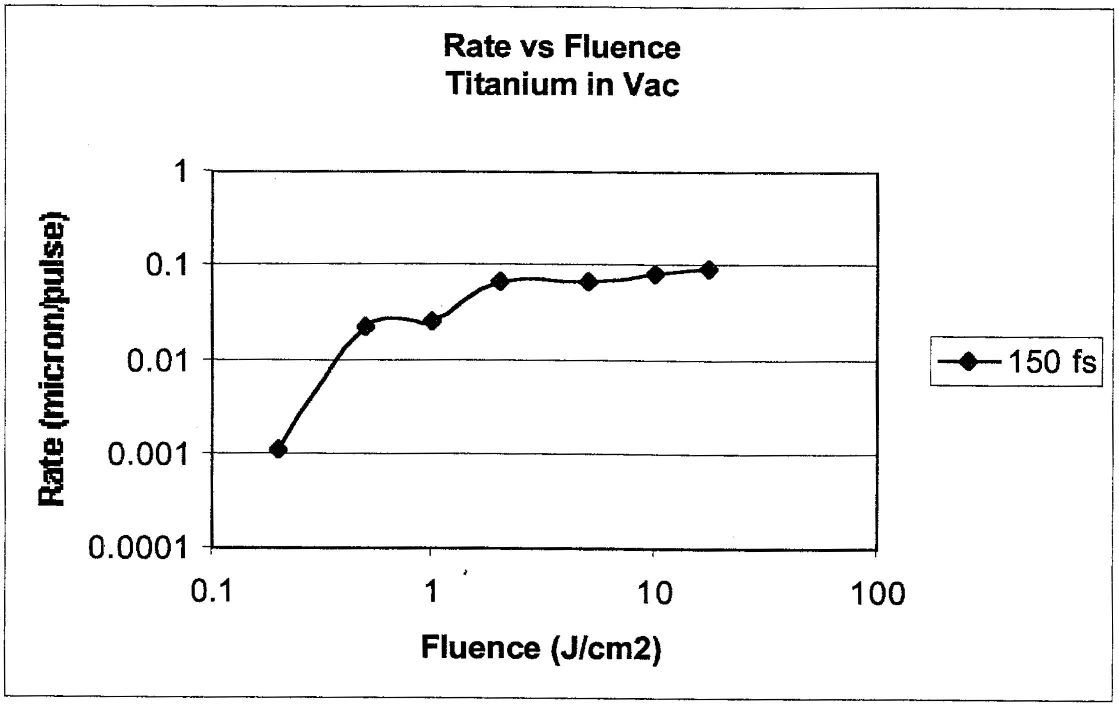

Rate vs Depth
Rhenium, 1.5 ps in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0
20
40
60
Depth (micron)
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.3 J/cm2

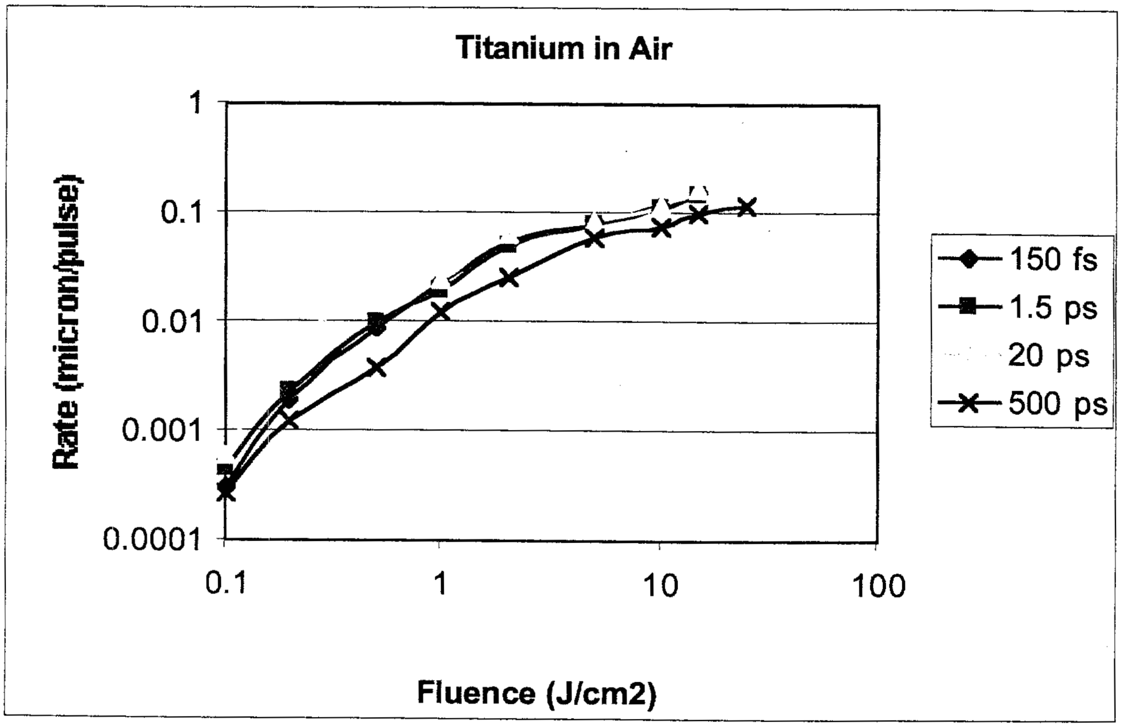

Rate vs Depth
Rhenium, 20 ps in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0
20
40
60
80
100
Depth (micron)
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.3 J/cm2

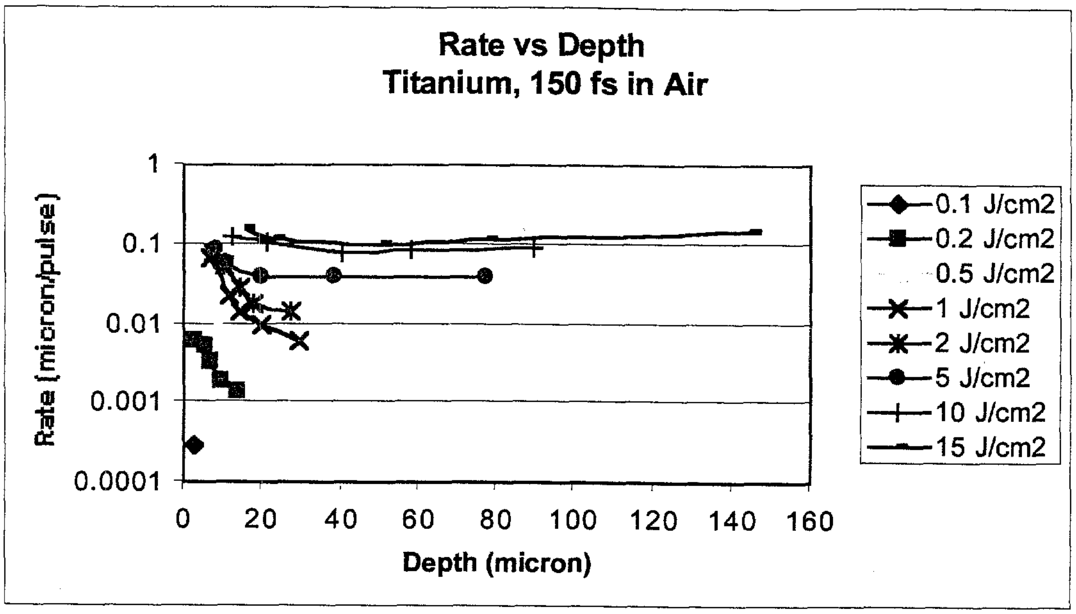

Rate vs Depth
Rhenium 500 ps in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0.0001
0
20
40
60
Depth (micron)
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.3 J/cm2
25.3 J/cm2

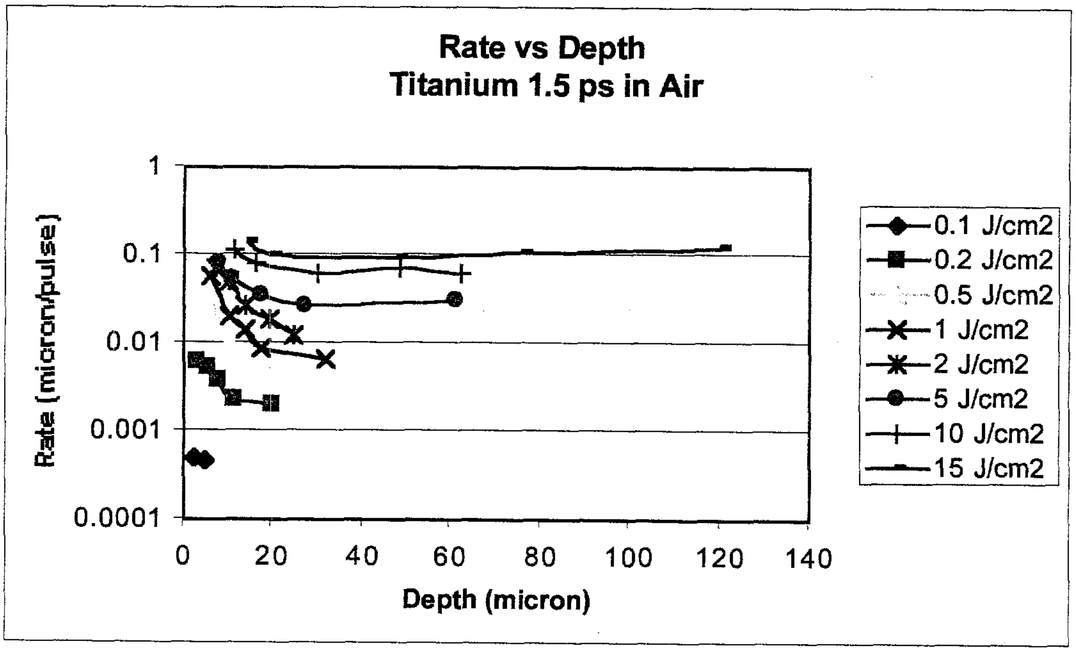

Rate vs Fluence
Rhenium 532 nm
Rate (micron/pulse)
10
1
0.1
0.01
1
10
100
Fluence (J/cm2)
200 ns

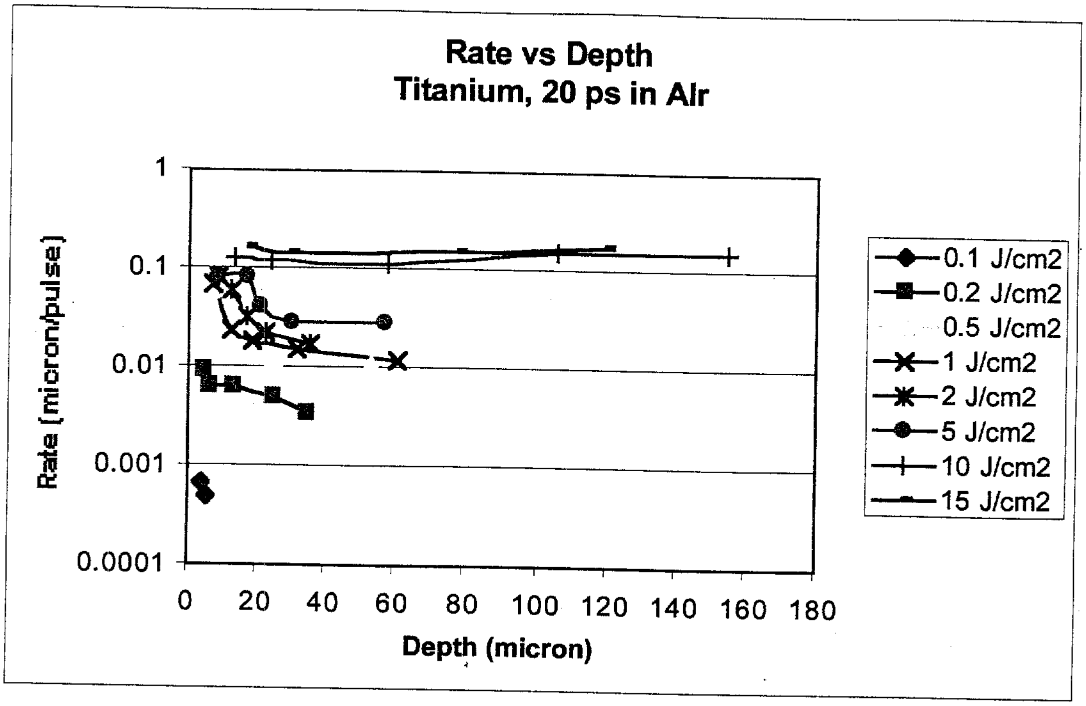
Titanium

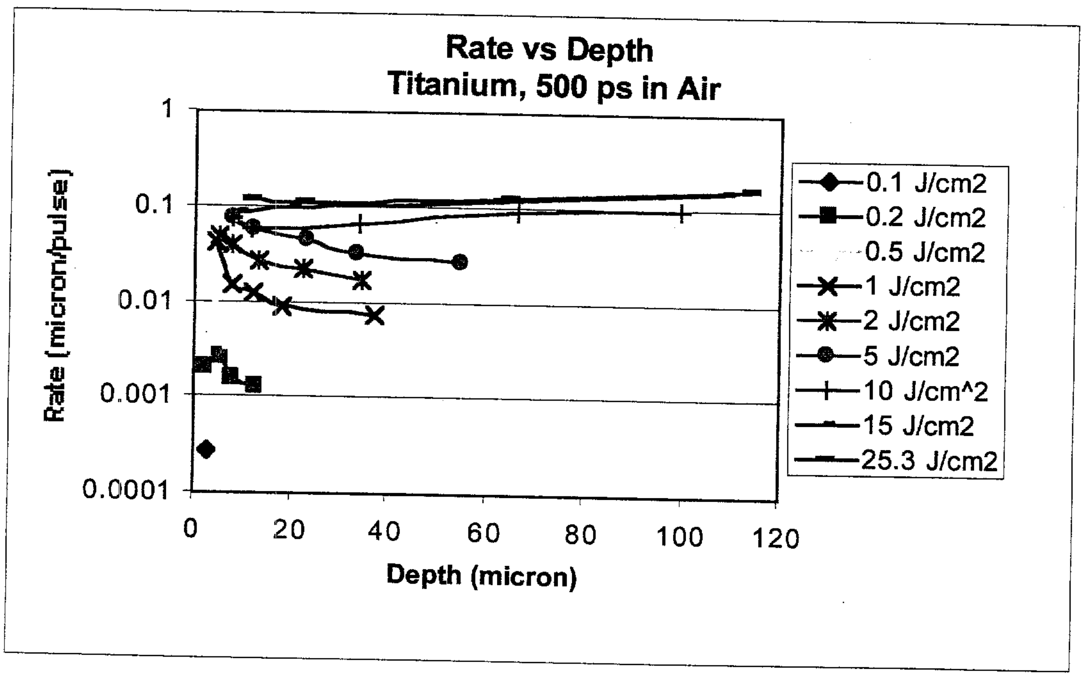

Rate vs Fluence
Titanium in Vac
Rate (micron/pulse)
1
0.1
0.01
0.001
0.0001
0.1
1
10
100
Fluence (J/cm2)
150 fs

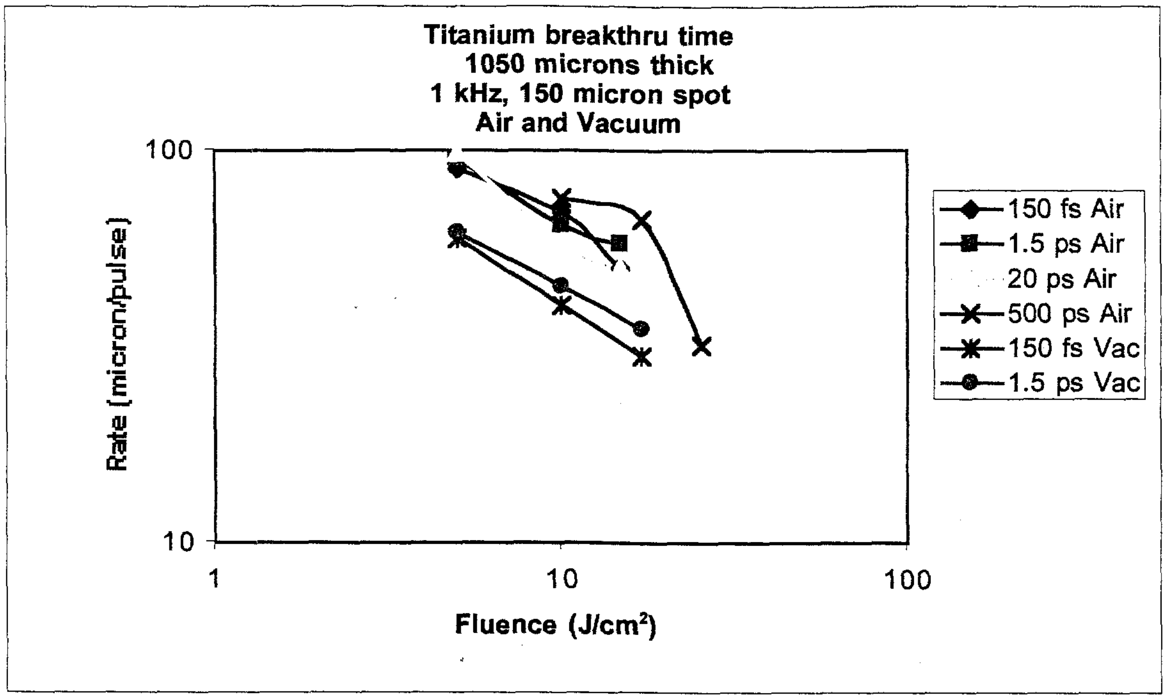

Titanium in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0.0001
0.1
1
10
100
Fluence (J/cm2)
150 fs
1.5 ps
20 ps
500 ps

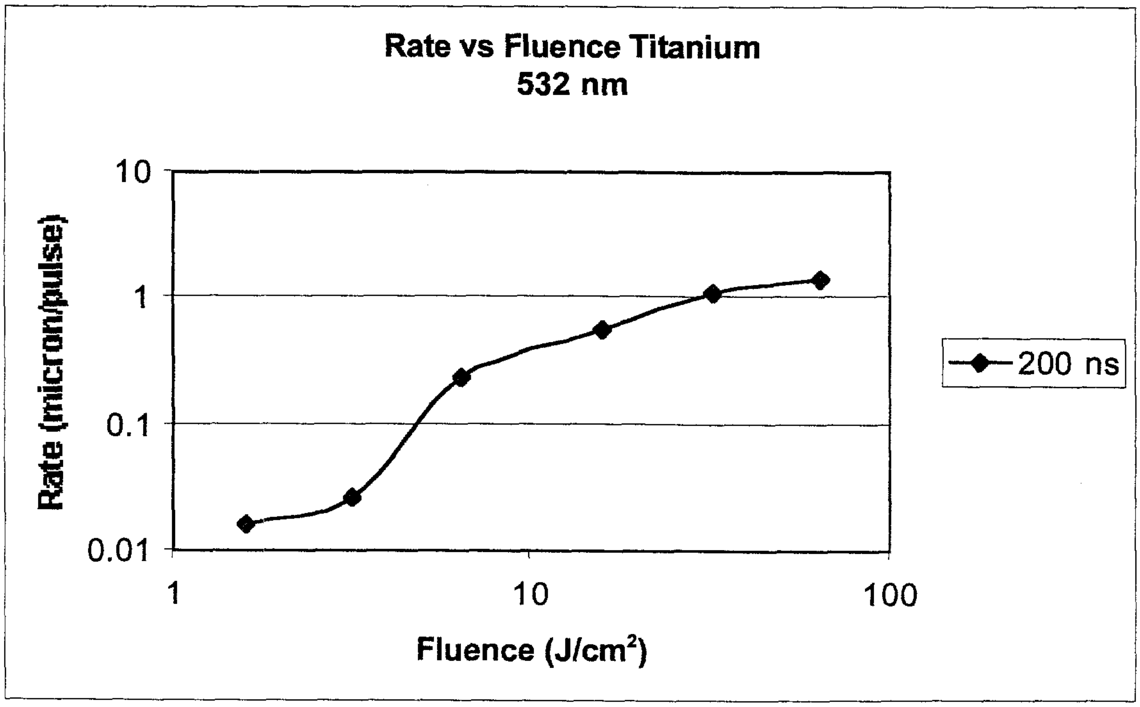

Rate vs Depth
Titanium, 150 fs in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0.0001
0
20
40
60
80
100
120
140
160
Depth (micron)
0.1 J/cm2
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
15 J/cm2


Rate vs Depth
Titanium 1.5 ps in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0.0001
0
20
40
60
80
100
120
140
Depth (micron)
0.1 J/cm2
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
15 J/cm2

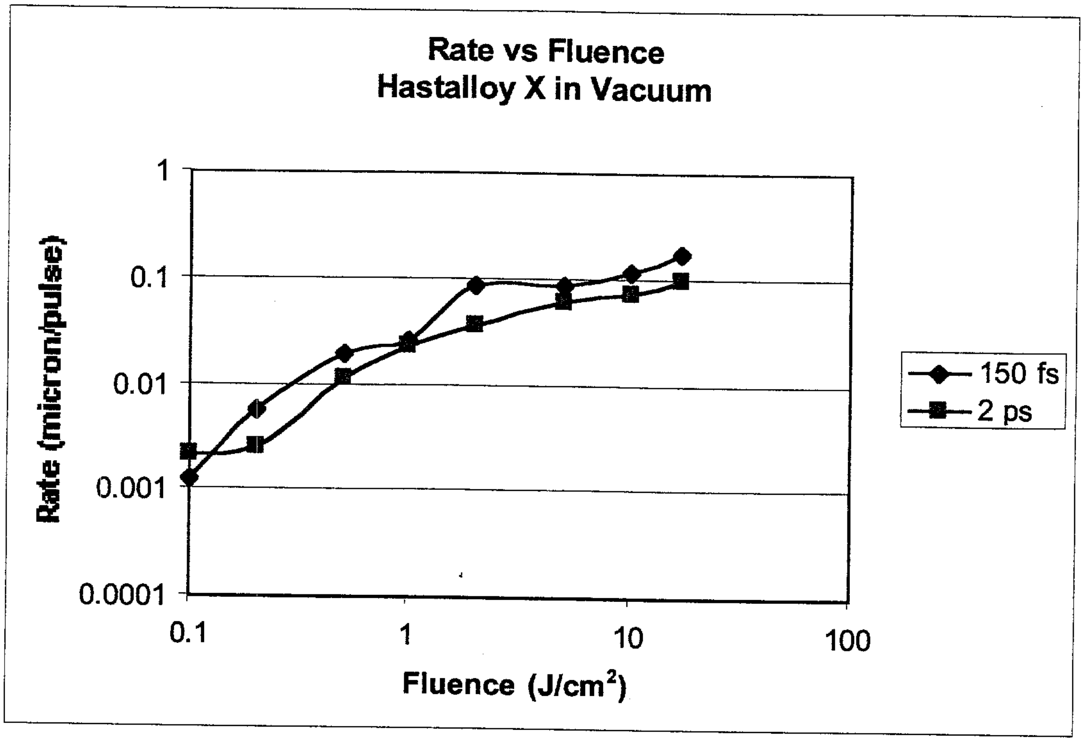

Rate vs Depth
Titanium, 20 ps in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0.0001
0
20
40
60
80
100
120
140
160
180
Depth (micron)
0.1 J/cm2
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
15 J/cm2

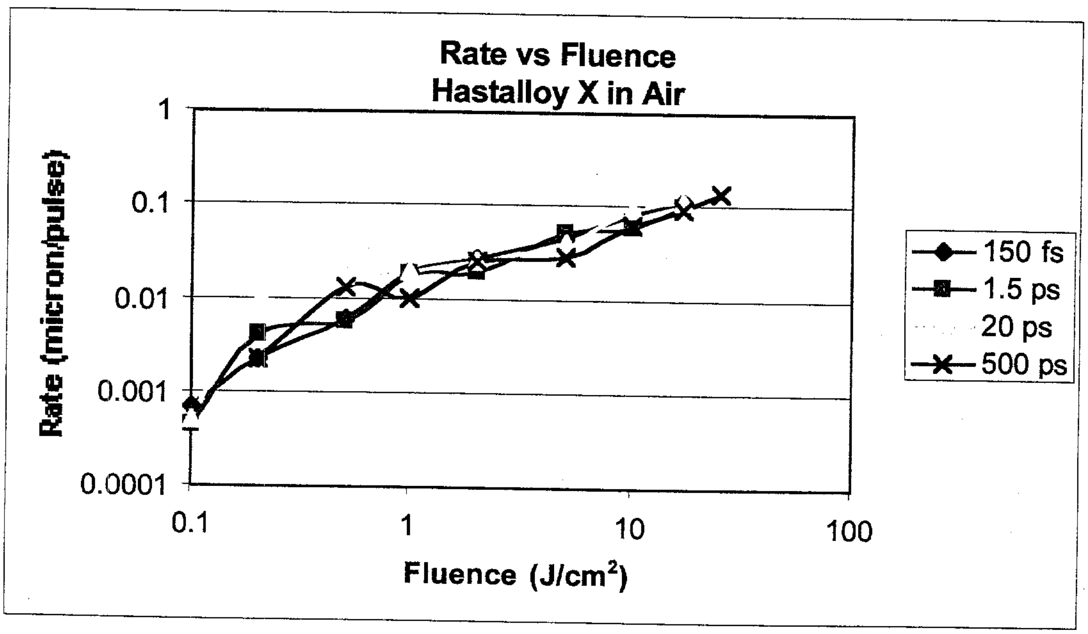

Rate vs Depth
Titanium, 500 ps in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0.0001
0
20
40
60
80
100
120
Depth (micron)
0.1 J/cm2
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm^2
15 J/cm2
25.3 J/cm2

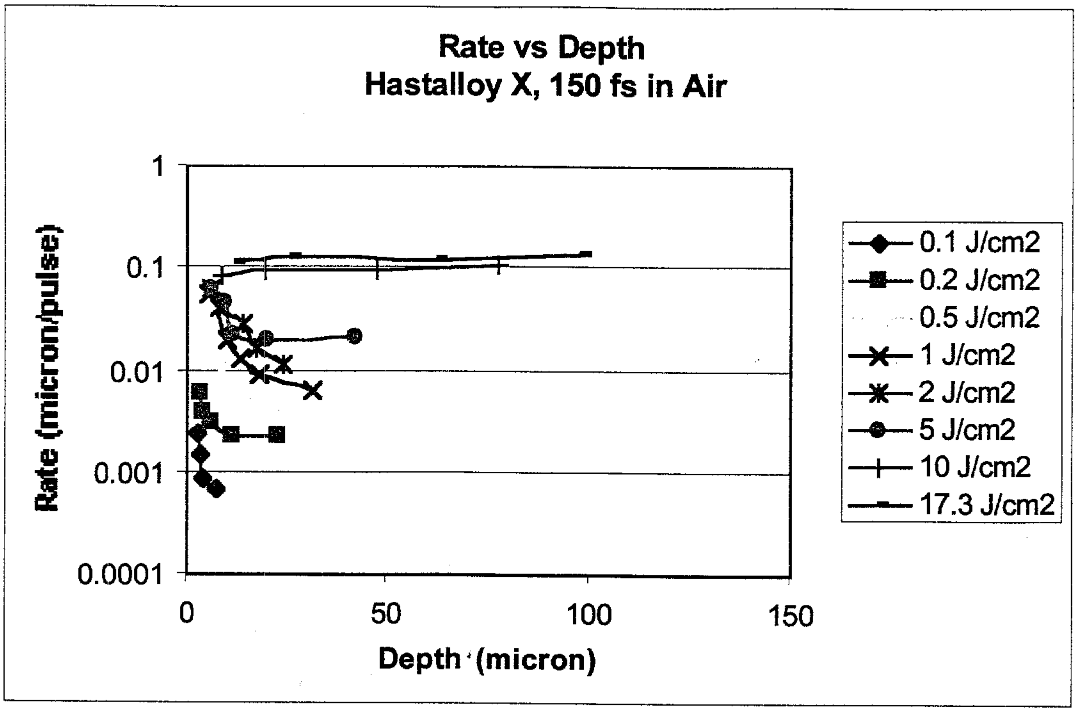

Titanium breakthru time
1050 microns thick
1 kHz, 150 micron spot
Air and Vacuum
100
10
1
10
100
Rate (micron/pulse)
Fluence (J/cm²)
150 fs Air
1.5 ps Air
20 ps Air
500 ps Air
150 fs Vac
1.5 ps Vac

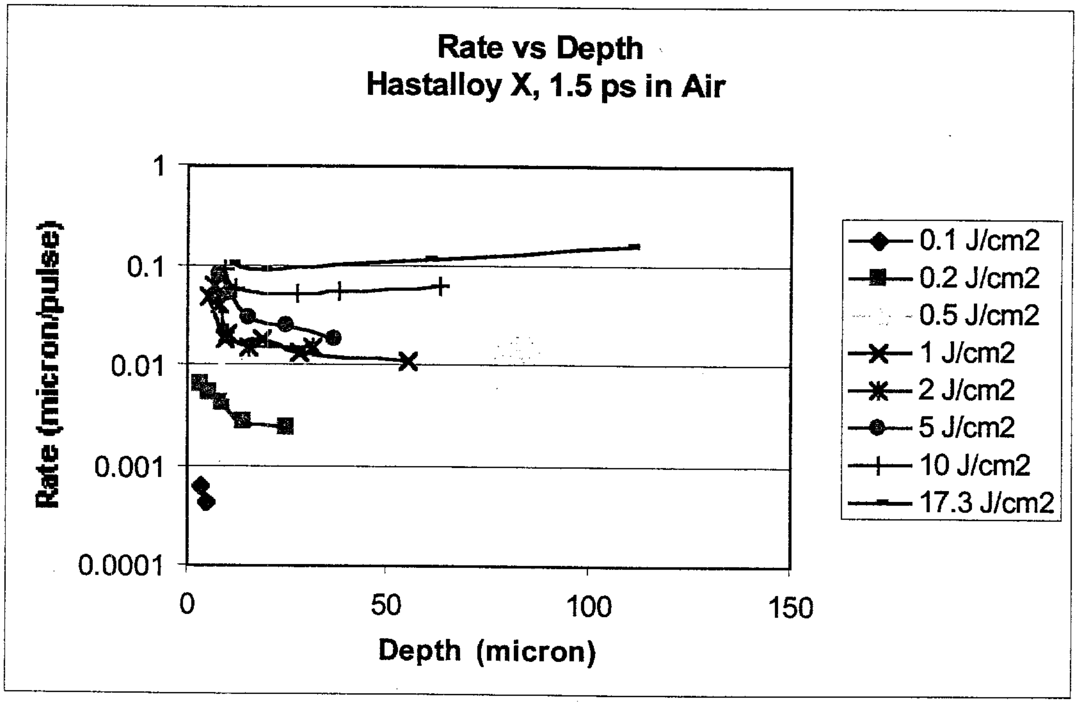

Rate vs Fluence Titanium
532 nm
10
1
0.1
0.01
1
10
100
Rate (micron/pulse)
Fluence (J/cm²)
200 ns

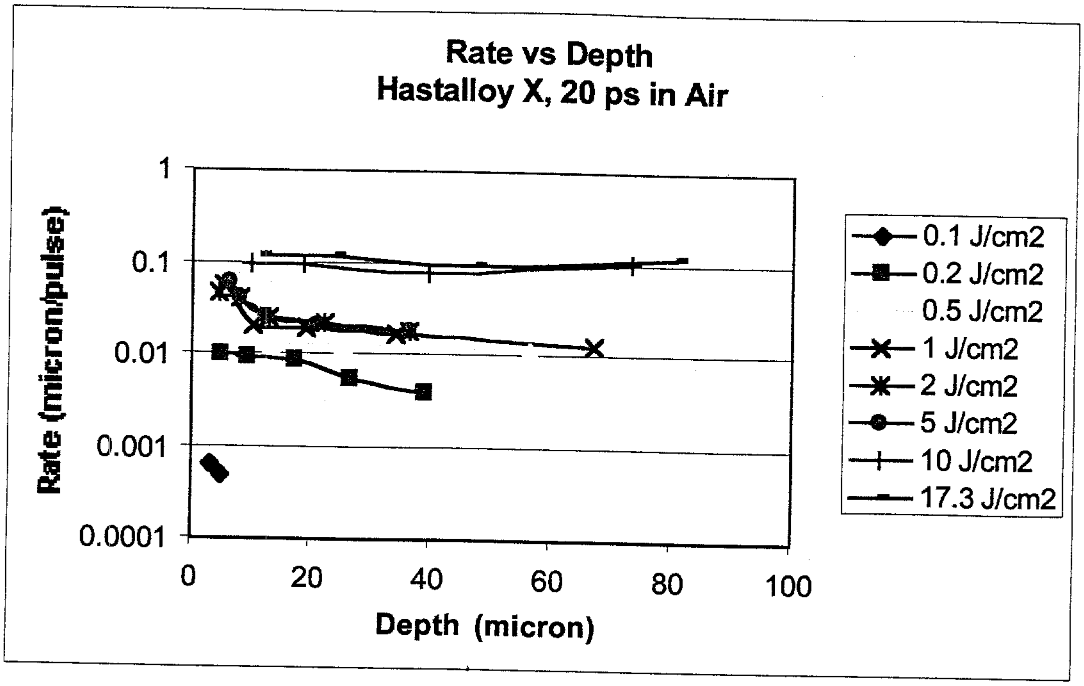
Hastalloy X

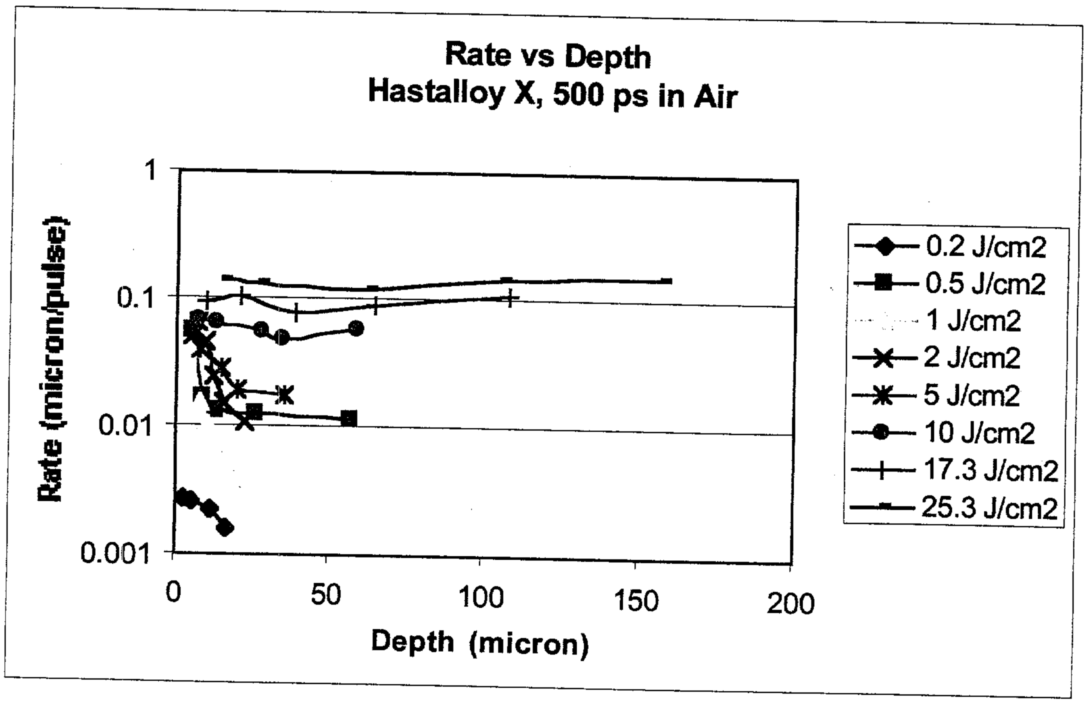

Rate vs Fluence
Hastalloy X in Vacuum
Rate (micron/pulse)
1
0.1
0.01
0.001
0.0001
0.1
1
10
100
Fluence (J/cm²)
150 fs
2 ps

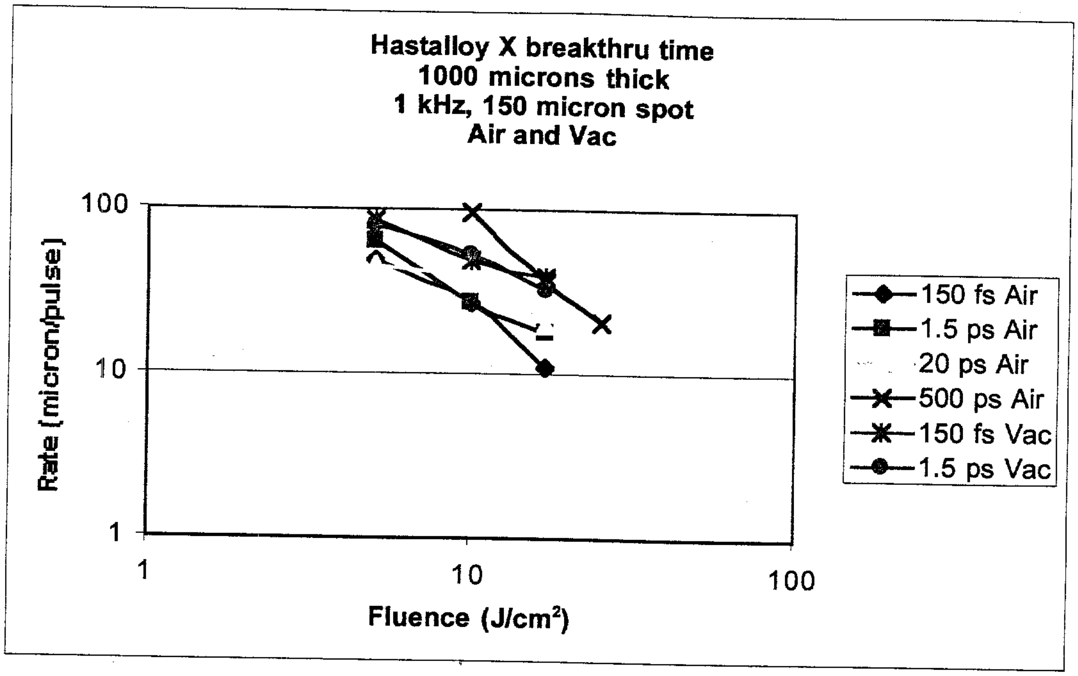

Rate vs Fluence
Hastalloy X in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0.0001
0.1
1
10
100
Fluence (J/cm²)
150 fs
1.5 ps
20 ps
500 ps

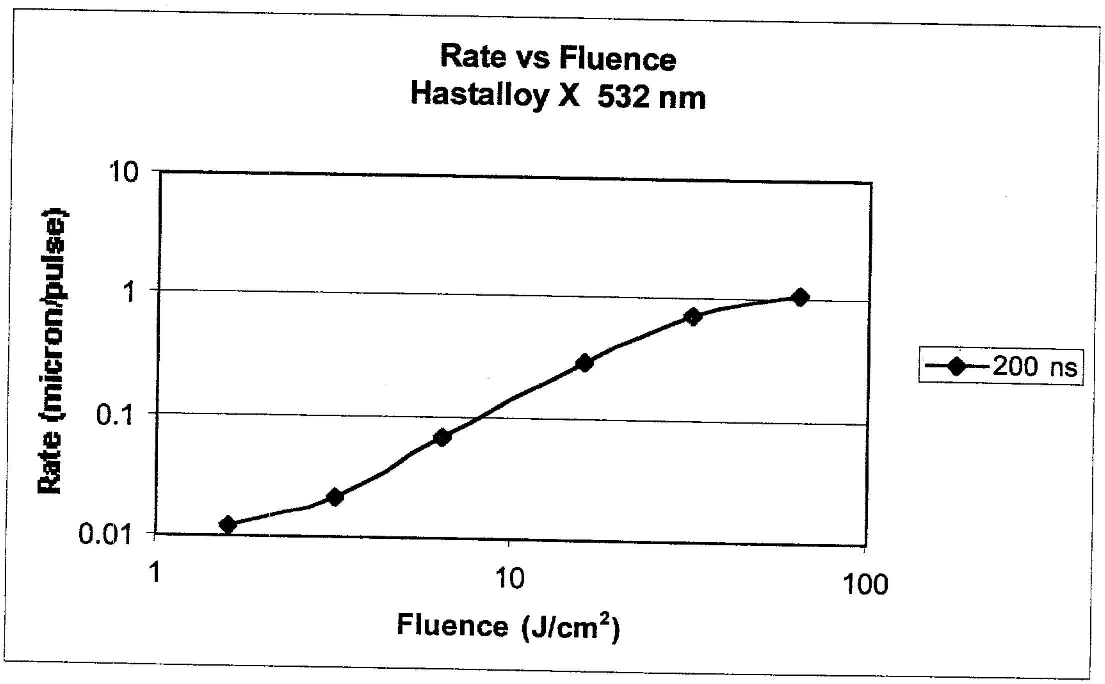

Rate vs Depth
Hastalloy X, 150 fs in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0.0001
0
50
100
150
Depth (micron)
0.1 J/cm2
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.3 J/cm2


Rate vs Depth
Hastalloy X, 1.5 ps in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0.0001
0
50
100
150
Depth (micron)
0.1 J/cm2
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.3 J/cm2

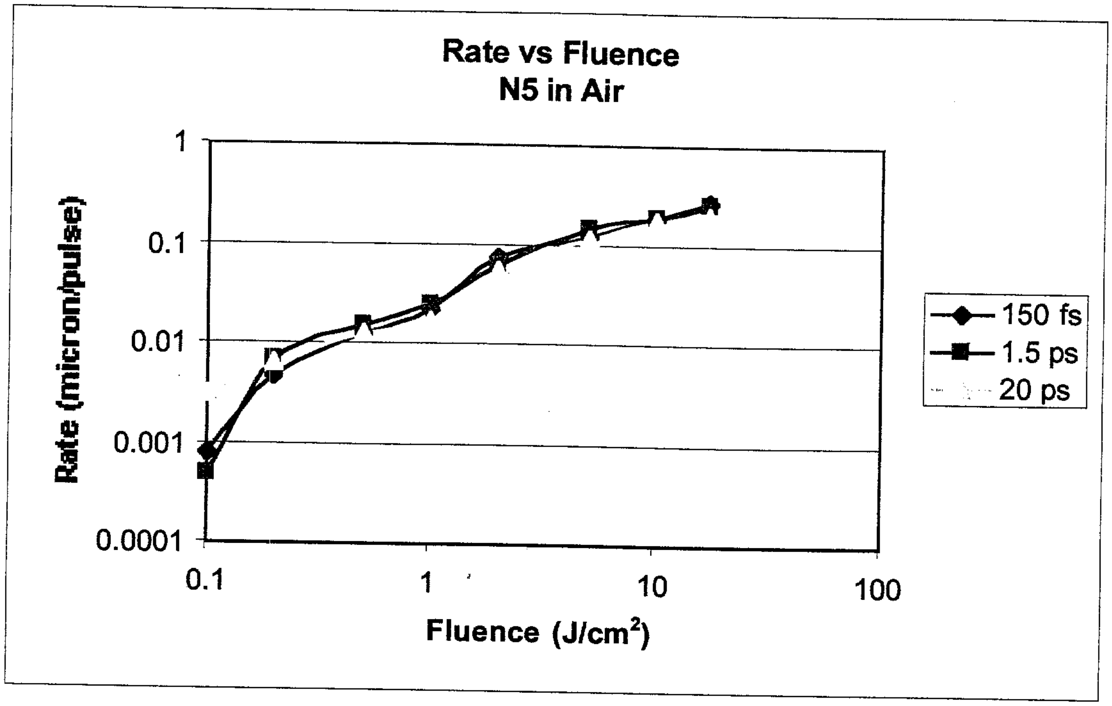

Rate vs Depth
Hastalloy X, 20 ps in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0.0001
0
20
40
60
80
100
Depth (micron)
0.1 J/cm2
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.3 J/cm2


Rate vs Depth
Hastalloy X, 500 ps in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0
50
100
150
200
Depth (micron)
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.3 J/cm2
25.3 J/cm2

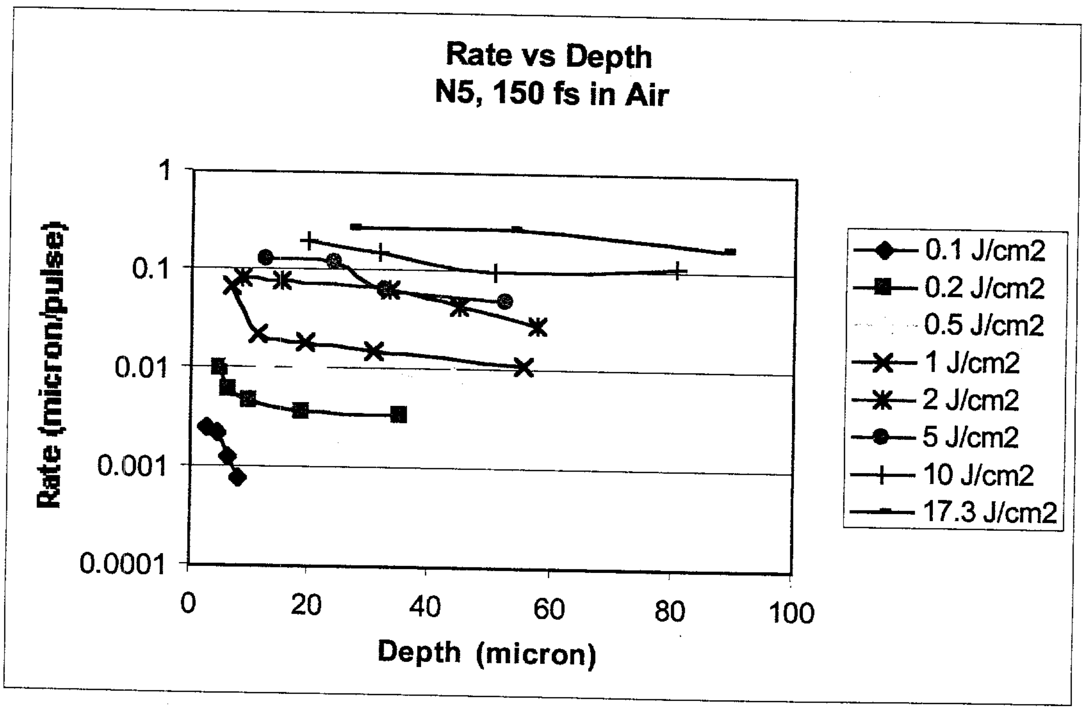

Hastalloy X breakthru time
1000 microns thick
1 kHz, 150 micron spot
Air and Vac
Rate (micron/pulse)
100
10
1
1
10
100
Fluence (J/cm²)
150 fs Air
1.5 ps Air
20 ps Air
500 ps Air
150 fs Vac
1.5 ps Vac


Rate vs Fluence
Hastalloy X 532 nm
Rate (micron/pulse)
10
1
0.1
0.01
1
10
100
Fluence (J/cm²)
200 ns

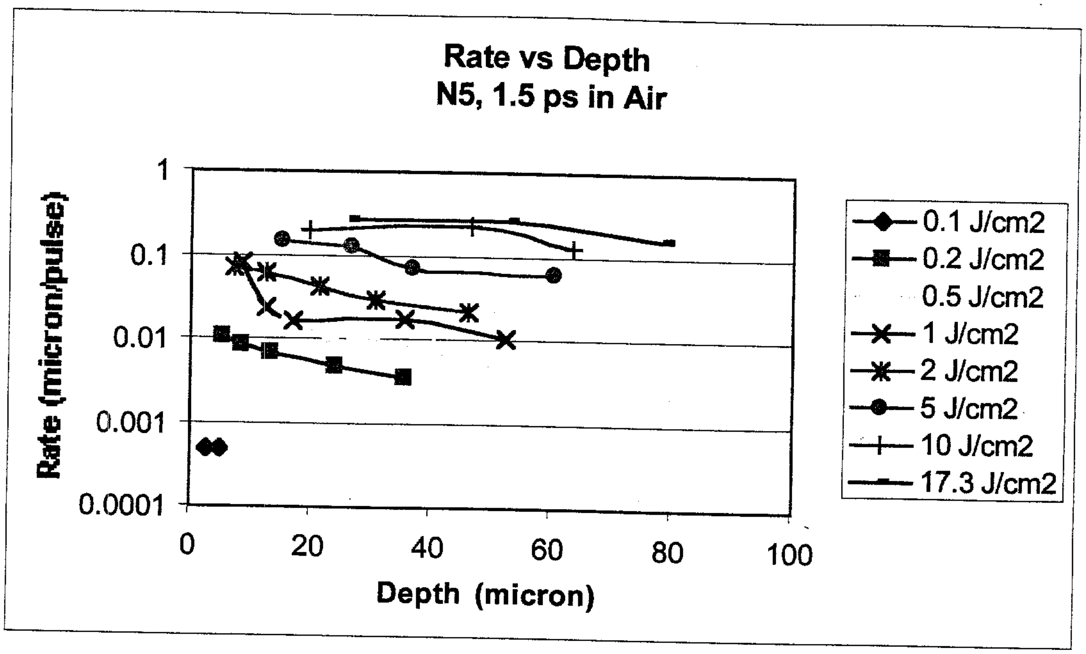
N5



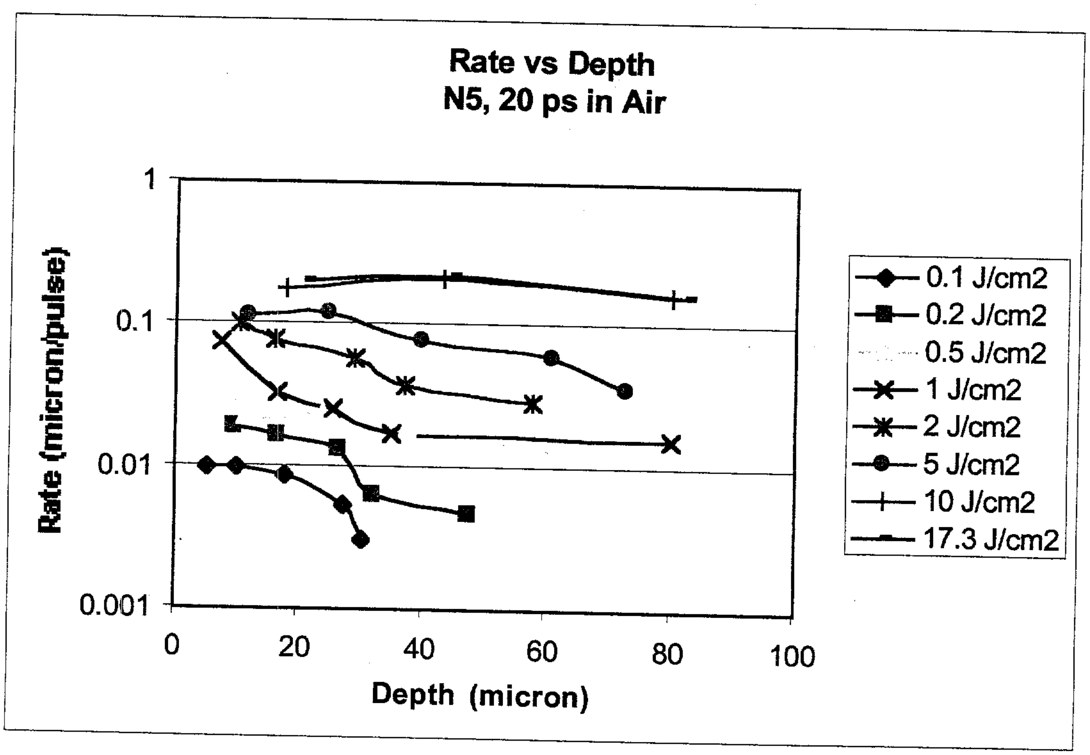
Rate vs Fluence
N5 in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0.0001
0.1
1
10
100
Fluence (J/cm²)
150 fs
1.5 ps
20 ps



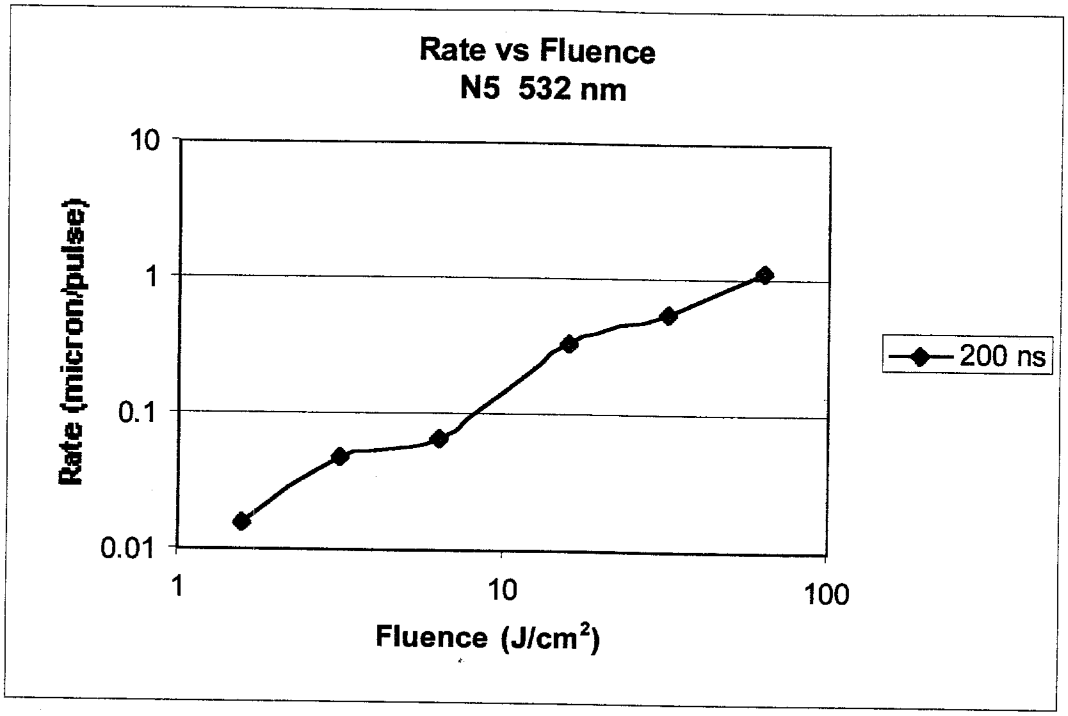
Rate vs Depth
N5, 150 fs in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0.0001
0
20
40
60
80
100
Depth (micron)
0.1 J/cm2
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.3 J/cm2



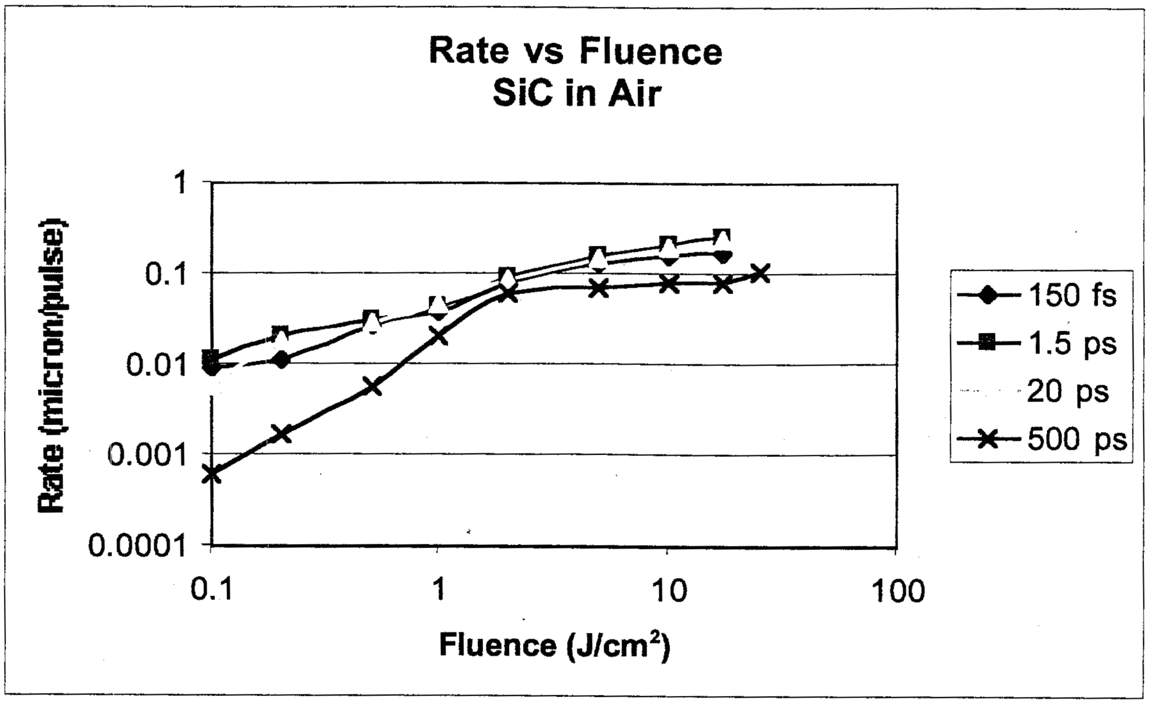
Rate vs Depth
N5, 1.5 ps in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0.0001
0
20
40
60
80
100
Depth (micron)
0.1 J/cm2
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.3 J/cm2

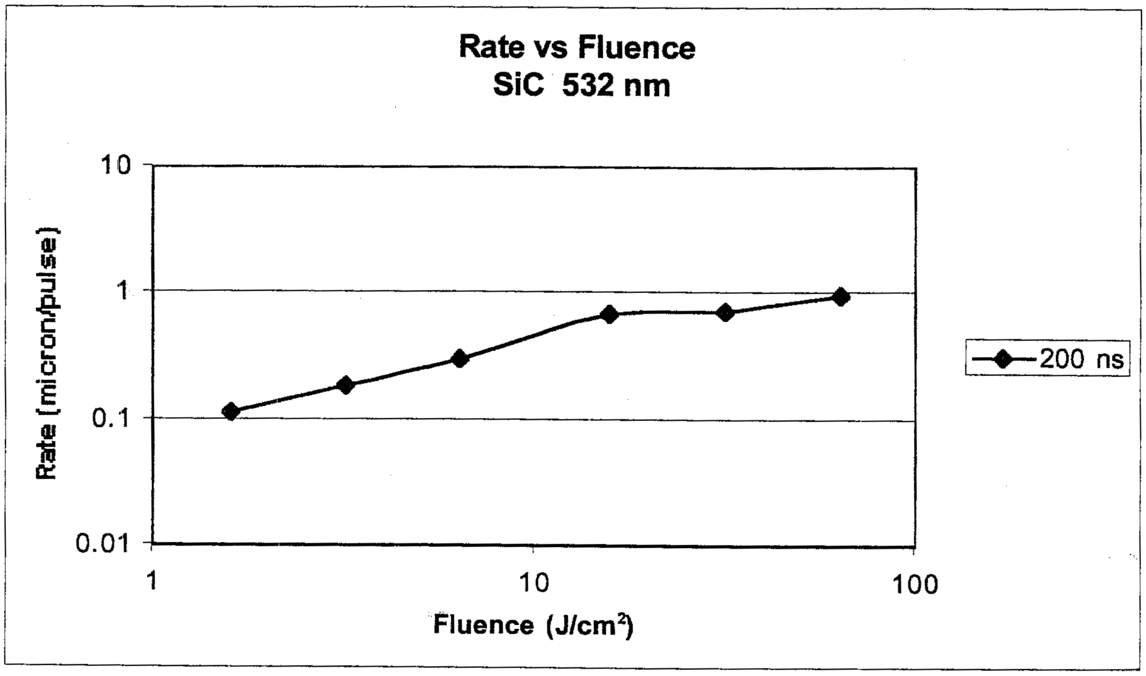


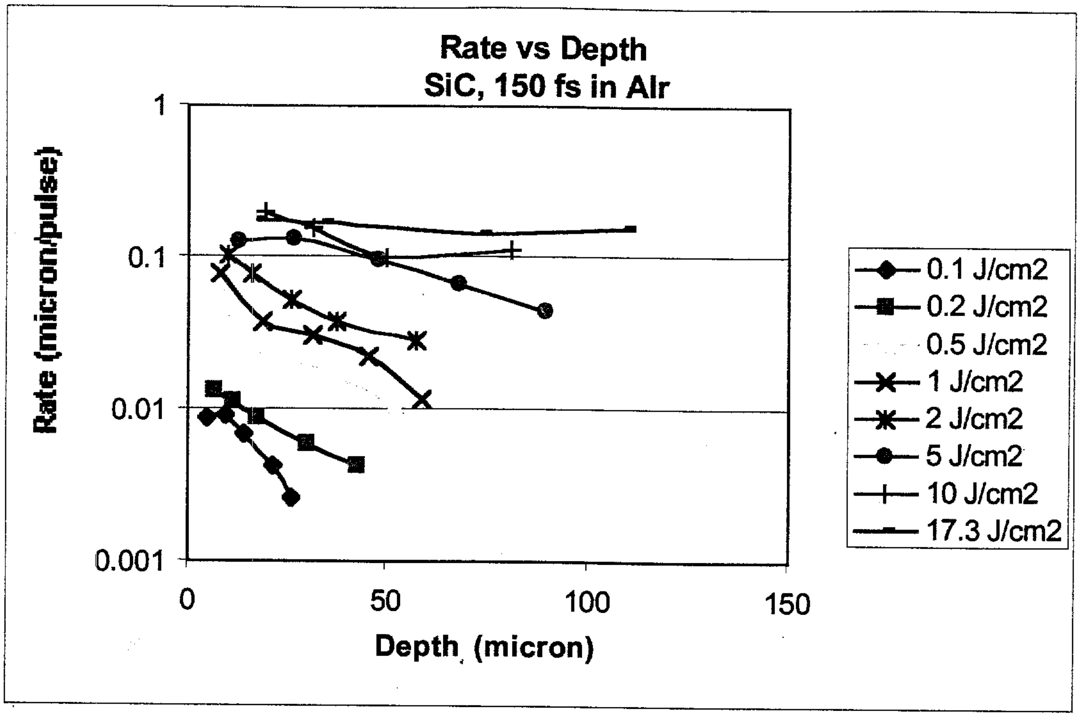
Rate vs Depth
N5, 20 ps in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0
20
40
60
80
100
Depth (micron)
0.1 J/cm2
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.3 J/cm2

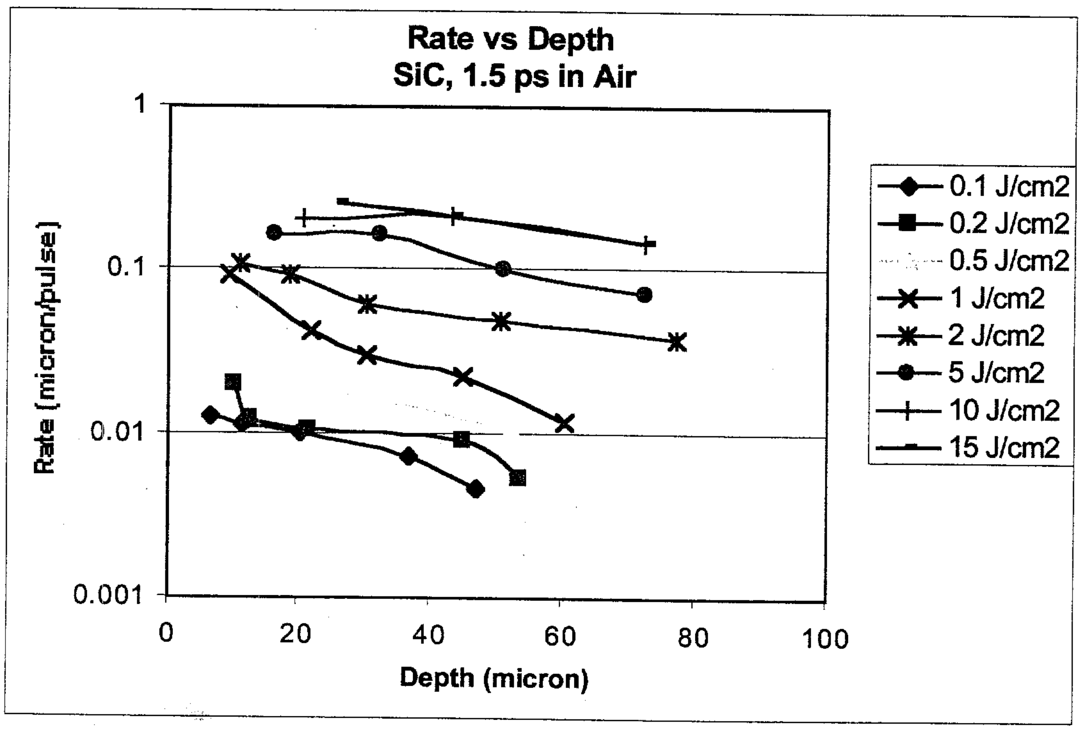

Rate vs Fluence
N5 532 nm
Rate (micron/pulse)
10
1
0.1
0.01
1
10
100
Fluence (J/cm²)
200 ns

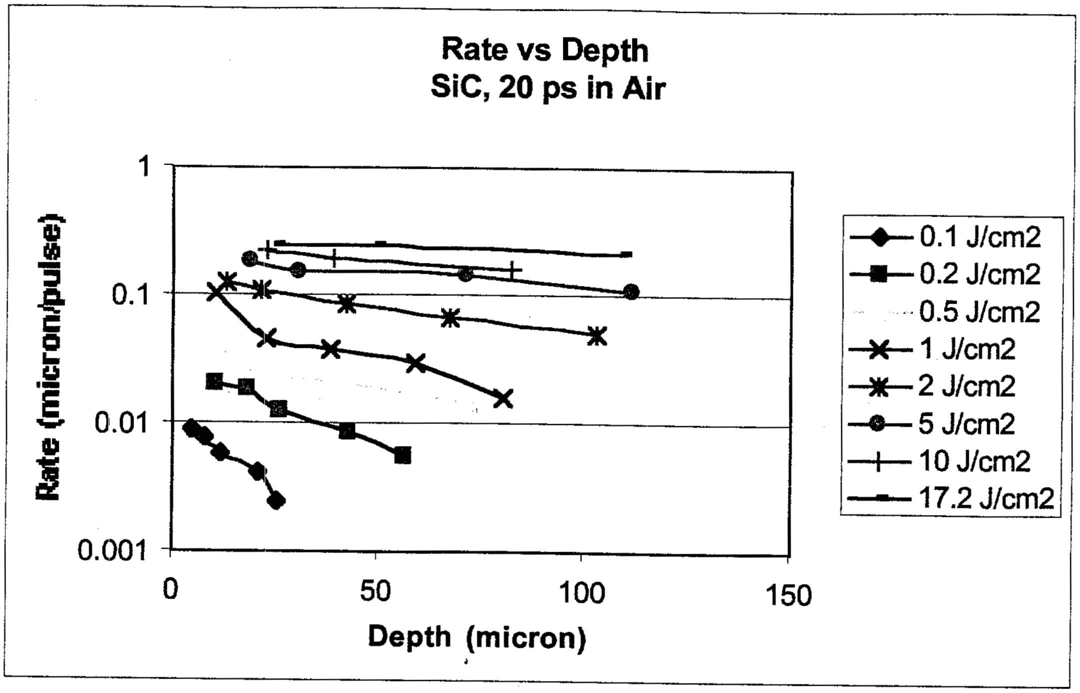
Silicon Carbide

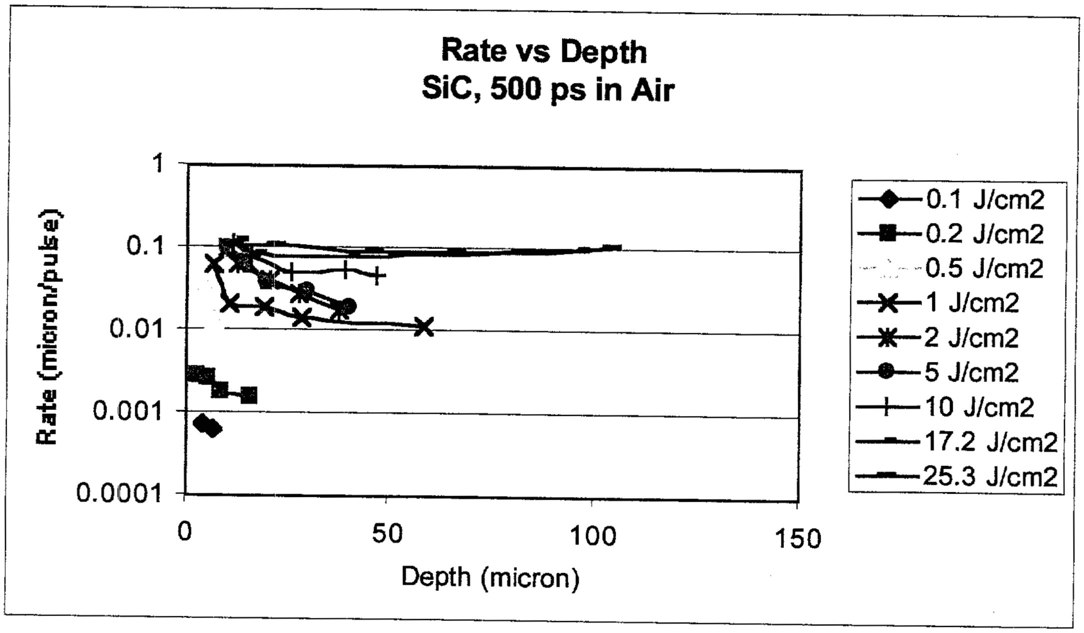


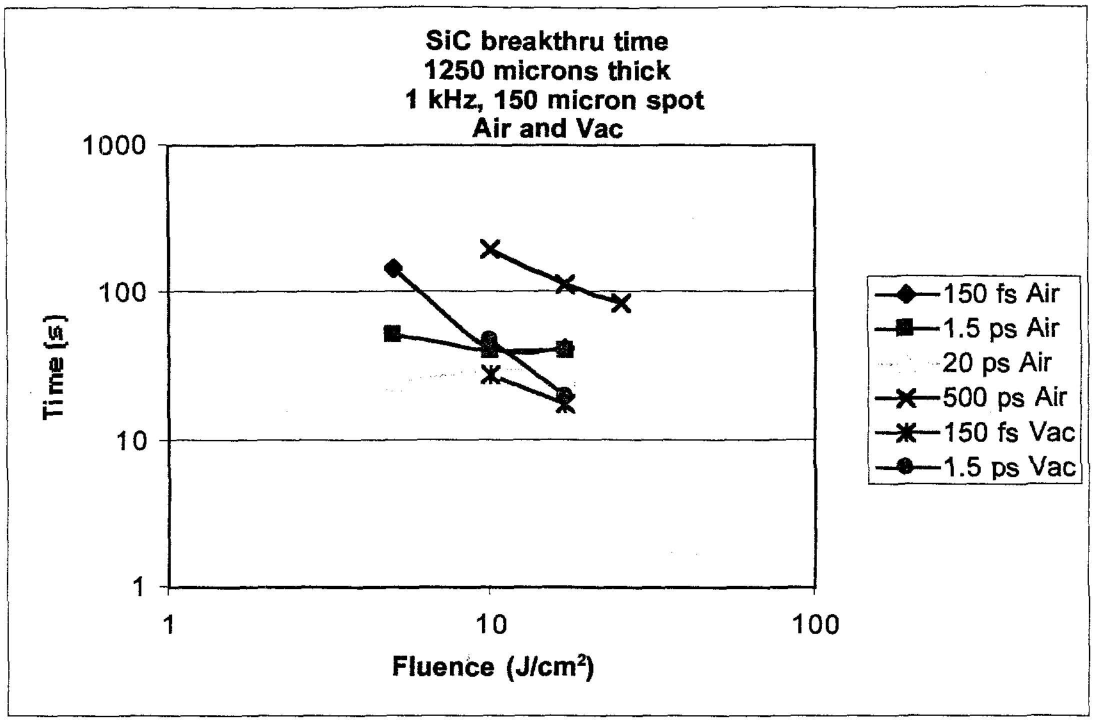



Rate vs Depth
SiC, 150 fs in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0
50
100
150
Depth (micron)
0.1 J/cm2
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.3 J/cm2


Rate vs Depth
SiC, 1.5 ps in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0
20
40
60
80
100
Depth (micron)
0.1 J/cm2
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
15 J/cm2


Rate vs Depth
SiC, 20 ps in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0
50
100
150
Depth (micron)
0.1 J/cm2
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.2 J/cm2


Rate vs Depth
SiC, 500 ps in Air
Rate (micron/pulse)
1
0.1
0.01
0.001
0.0001
0
50
100
150
Depth (micron)
0.1 J/cm2
0.2 J/cm2
0.5 J/cm2
1 J/cm2
2 J/cm2
5 J/cm2
10 J/cm2
17.2 J/cm2
25.3 J/cm2


SiC breakthru time
1250 microns thick
1 kHz, 150 micron spot
Air and Vac
1000
100
10
1
Time (s)
1
10
100
Fluence (J/cm²)
150 fs Air
1.5 ps Air
20 ps Air
500 ps Air
150 fs Vac
1.5 ps Vac

Discussion

We found that the laser pulse-width did not have any significant effect on initial ablation rate. There was also little noticeable difference in initial ablation rate while comparing air and vacuum. The shapes of the curves were similar and the rates were slightly lower in air. However, the effects of a vacuum environment were quite apparent when drilling through thick (1 mm) samples at high aspect ratios as discussed in a later section.

We found a strong dependence of ablation rate on depth of the hole. Channel formation and increasing roughness of the bottom of the hole with an increasing number of pulses can explain this reduction of ablation rate with depth of the hole.

At low fluences, we believe that increasing roughness with increasing number of pulses is one of the causes of the reduction of ablation rate. Also, as the angle of the walls of the hole increases, the rate will decrease due to the laser fluence on the walls dropping below ablation threshold. At high fluences, the rate decreases up to a certain depth and then increases again. This is explained by the formation of the central channel in the bottom of the hole that has a much faster ablation rate than the rest of the hole. This seems to occur at depths greater than 40 microns and at fluences greater than 5 J/cm^2.

Breakthrough times measured were generally shorter in vacuum than in air for most materials. This is due to channel formation as well as lack of laser-air interaction in a vacuum.

Below are tables of initial ablation rates at select pulse widths and fluences:

Rates at 150 fs (810 nm)

	Fluence = 1 J/cm^2		Fluence = 10 J/cm^2	
Material	Rate in Air	Rate in Vac	Rate in Air	Rate in Vac
Stainless	0.022 μm/pulse	0.025 μm/pulse	0.09875 μm/pulse	0.098μm/pulse
Rhenium	0.018μm/pulse	0.019 μm/pulse	0.085 μm/pulse	0.079 μm/pulse
Titanium	0.023 μm/pulse	0.025 μm/pulse	0.12 μm/pulse	0.085 μm/pulse
N5	0.022 μm/pulse		0.195 μm/pulse	
Hastalloy X	0.019 μm/pulse	0.026 μm/pulse	0.085 μm/pulse	0.12 μm/pulse
SiC	0.038 μm/pulse		0.15625 μm/pulse	

Rates at 500 ps (810 nm)

	Fluence = 1 J/cm^2		Fluence = 10 J/cm^2	
Material	Rate in Air	Rate in Vac	Rate in Air	Rate in Vac
Stainless	0.0095 μm/pulse	0.018μm/pulse	0.049μm/pulse	0.11μm/pulse
Rhenium	0.0059μm/pulse		0.049μm/pulse	
Titanium	0.012 μm/pulse		0.078μm/pulse	
Hastalloy X	0.011 μm/pulse		0.066 μm /pulse	
SiC	0.021 μm/pulse		0.08 μm/pulse	

Green Rates (532 nm)

	Fluence = 1.6 J/cm^2	Fluence = 16 J/cm^2
Material	Rate	Rate
Stainless	0.028 μm/pulse	0.75 μm/pulse
Rhenium	0.023 μm/pulse	0.16 μm/pulse
Titanium	0.017 μm/pulse	0.58 μm/pulse
N5	0.016 μm/pulse	0.34 μm/pulse
Hastalloy X	0.012 μm/pulse	0.3 μm/pulse
SiC	0.12 μm/pulse	0.68 μm/pulse

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.