



Lasers as Tools for Manufacturing II

**Leonard R. Migliore
Ronald D. Schaeffer**
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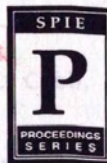
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Processing Parameters for Laser Micromachining

James Angell, Wen Ho, Jeff Bernstein, Ronald D. Schaeffer

ABSTRACT

Over a period of many years a wealth of information has been accumulated on processing parameters for laser micromachining of different materials. This information includes threshold fluences, etch rates vs. fluence curves, taper effects, debris minimization and assist gas effects to name a few. It is the intent of the authors to compile this empirical information into an easily accessible catalog to be used as a reference guide for those interested in laser micromachining. Information will be included on material type, lasers used in machining (CO_2 , solid state, excimer), laser processing parameters (wavelength, fluence, pulse width, cutting speed) and other material related information (thickness, feature sizes, etc.)

keywords: micromachining, lasers, material processing, parameters

1. INTRODUCTION

Not long after the development of the first lasers it was discovered that they could be used as machining tools. Several advantages of using lasers over conventional machining tools were soon discovered. Laser machining is, of course, a non contact technique so there is no tool wear as there is with, say, the use of a lathe or a milling machine, and there is less contamination. The non contact nature of the laser also eliminates shock and stress to materials caused by the impact of machine tools, and it has been found that in many instances lasers are the preferred machining source for fragile materials such as ceramics. Laser light can also be directed to hard to reach locations through fiber optic delivery and a robot arm. Thus, for example, holes can be drilled into different sides of a large awkwardly shaped part without the necessity of rotating the actual part.

The lasers with the most industrial experience are the CO_2 and Nd:YAG (Neodymium : Yttrium Aluminum Garnet). These lasers have both achieved a great deal of success and remain the most prevalent lasers in industry today. CO_2 and Nd:YAG lasers have, for some time, been incorporated into user friendly machines requiring the same degree of operator skill as a CNC milling machine. Indeed many hole drilling and cutting operations in high throughput applications such as those in the auto industry have replaced mills and lathes with lasers. They are very commonly used for machining metals, plastics, ceramics, and even wood. The light produced by CO_2 and Nd:YAG lasers is in the infrared region of the spectrum. Infrared lasers machine material by heating it to its melting or vaporization point and in most cases using a high pressure gas jet to assist with material removal. For many years the emphasis in laser development was on producing lasers with the highest power practical. The higher the power, the faster material could be machined. A great deal of information has been tabulated regarding the use of high power CO_2 and Nd:YAG lasers, and there is at least one commercially available database of processing parameters for them.¹ This information has been gleaned from the use of lasers which perform the same type of work as traditional industrial machines. Examples include Nd:YAG cutting of steel sheet stock and CO_2 cutting of plastic.

In the last ten years or so a new realm of laser machining has opened up which has been termed micromachining. It has coincided with the development of the excimer laser which produces light in the ultra violet region of the spectrum. The combination of UV light and other excimer laser properties to be discussed below make it suitable for machining much smaller, higher resolution, and higher quality features than is possible with infrared lasers. Excimer lasers and systems have, like CO_2 and Nd:YAG lasers, developed into industrial tools, though not nearly to the same extent as their predecessors. Compared to most high power CO_2 and Nd:YAG lasers, excimers are notoriously slow and high maintenance machines. Therefore, along with efforts to make excimers more powerful, i.e. faster, and more reliable, there have been efforts to improve the existing CO_2 and solid state technologies to enable these lasers to machine smaller, higher resolution, better quality features with as little cost to speed as possible. Examples include Q-switched solid state lasers and RF excited slab CO_2 lasers.

As micromachining lasers become more commonplace it makes sense to begin to catalog processing parameters into a usable format to serve as a reference to those interested in laser micromachining applications. The information included

should assist the applications developer in determining laser feasibility, as well as get them started establishing processing parameters and expected processing speeds. Particular parameters are laser dependent and will be discussed below. This paper will begin by reviewing the basics of three types of lasers: solid state, CO₂, and excimer and the processing parameters applicable to each. We will look at different classifications of materials based on the effect of different laser parameters. Then we will briefly discuss the different processing techniques associated with each laser and the methods of taking data. We will present samples of processing parameters for the different lasers and different classes of materials.

2. LASERS

2.1 CO₂

The most common industrial laser is the CO₂ laser. It comes in a wide variety of power outputs and is capable of machining many different types of materials including metal, plastic, wood, and glass. It is relatively low maintenance and can be incorporated into systems which are quite simple to operate. Over the last several years a few different manufacturers have introduced RF excited pulsed CO₂ lasers to the market. One of the most well known examples of these is the Coherent Diamond®. The maximum average power output of these lasers is typically 50 to 250 Watts. The pulse width and pulse repetition rate can be varied over a wide range making the average power output highly variable and capable of being distributed in different manners. That is, the average power is essentially a function of the pulse duty cycle so, for example, a pulse width of 50 microseconds combined with a period of 0.2 milliseconds produces approximately the same power as a pulse width of 500 microseconds combined with a period of 2 milliseconds. There is, of course, some variation because there is a slight variation of peak power with pulse width, but this is usually a negligible effect in practice. Thus there is a wide range of laser parameters which an applications engineer can use to achieve a desired processing effect. These lasers have also been equipped with a proprietary optical configuration which produces a beam with M² less than 1.5, so the beam can, with the appropriate lens, be focused to about a 50 micron spot without too much difficulty. Also Coherent's pulsing mechanism produces light pulses with very fast rise and fall times, that is, nearly square pulses. The square pulse, Coherent claims, allows for most of the pulse energy to be above a material's ablation threshold. Therefore almost all the energy is working to remove material instead of just heat it up. The combination of the square pulse and the low M² allow these lasers to produce smaller features with less heat affected zone than many of the traditional slow flow CO₂ lasers, making them more suitable to micromachining.

With regard to machining, the CO₂ is primarily a cutting and drilling laser. The speed at which it can produce holes and cuts is, of course, dependent on the type and thickness of material. Our catalog of processing parameters should therefore include material type, thickness, average laser power, pulse width, pulse period, focused spot size, gas assist pressure, and processing speed. We also want to include any side effects that should be expected from the machining process such as the presence of dross, which is resolidified material on the laser exit side of the material.

2.2 Solid State

A drawback to the CO₂ lasers discussed above is that they do not produce a high enough peak power density to efficiently machine certain types of materials. These include highly reflective metals such as Aluminum and Copper, and refractory metals such as Tantalum. A Q-switched solid state laser of only 10-15 Watts average power can produce a peak power density up to two orders of magnitude greater than many 100 - 150 Watt CO₂ lasers. While a 10 Watt Q-switched laser produces a pulse which is much lower in energy than that of a 100 Watt CO₂, the Q-switched pulses are only about one ten-thousandth the duration in time, thus producing a much higher peak power. We have found that a Q-switched Nd:YLF (Neodymium: Yttrium, Lithium, Fluoride) laser, which produces radiation at 1.047 μm , is highly effective at machining metal foils such as Tantalum and CVD diamond of thickness up to about 1mm. The CO₂ laser is also ineffective on materials that are transparent at infrared wavelengths. An advantage of the solid state laser thus lies in its capability of being frequency doubled, tripled, or quadrupled. For example, a Nd:YLF laser that is frequency doubled to produce green light can machine Zinc Selenide with very fine precision.

The solid state laser is, like the CO₂, primarily a cutting and drilling laser. The relevant processing parameters are therefore, the same as those for the CO₂, although there is often no variation in pulse width and an assist gas is usually not required.

2.3 Excimer

The excimer laser, unlike the CO₂ and solid state Nd:YLF, emits radiation in the ultra-violet region of the spectrum. The exact wavelength is dependent on the gas used in the laser. The following are the most common excimer gases and their

corresponding wavelengths: Krypton Fluoride - 248 nm, Argon Fluoride - 193 nm, Xenon Chloride - 308 nm. The excimer gas is mixed in low concentration with a buffer gas such as neon inside the laser head. Excimer lasers typically emit pulses of constant duration of about 15 - 20 nanoseconds. High power excimer lasers typically generate up to 80 Watts in various configurations of pulse energy and pulse repetition rate. For example, one 80 Watt excimer may produce 200 millijoule pulses at repetition rates up to 400 pulses per second, while another may produce 800 millijoule pulses at rep. rates up to 100 pulses per second. The beam profile of the excimer laser is commonly characterized as top-hat in one direction and near Gaussian in the other and has a cross section that is normally about 5 mm by 15 mm and of nearly uniform intensity.

In excimer processing a mask imaging technique is often employed, in which a mask of the desired feature shape is inserted in the beam path and then reduced in magnification and imaged onto the work surface by appropriate focusing optics. The size and shape of the beam spot at the work surface is therefore a function of the mask and the demagnification. These two factors along with laser output pulse energy are what largely determine the energy density at the work surface. The energy density per pulse, or fluence, is expressed in Joules per square centimeter (J/cm^2). Though the actual material removal mechanism is dependent on the type of material (metal, ceramic, plastic, glass) all materials except those that are UV transmitting have what is referred to as an ablation threshold. This is the fluence below which a material is unaffected and above which a material begins to ablate. Ablation refers to the process of material removal through photodecomposition or vaporization. The depth of material removed per laser pulse is a function of fluence as pictured in figure 1. The etch rate increases in a nearly linear fashion above threshold until a plateau is reached. The most efficient processing fluence is on the plateau, since, in practice, there will always be some fluctuation in fluence due to laser energy fluctuations; and if one is on the linear portion of the curve these fluctuations will result in variations in the amount of material removed during an operation. This could result, for example, in through holes not penetrating completely, or a groove which is too deep or not deep enough.

The excimer laser is commonly used, not only for cutting and drilling, but also for producing blind features as well as features of any imaginable shape. The top hat beam profile and imaging technique enable the user to make blind features with flat bottom surfaces, unlike the V-shaped bottom typical of beams with a pure gaussian profile. It is, therefore, appropriate to refer to the etch rate per pulse, usually in microns, rather than a cutting or drilling rate. Along with this we need to know a materials ablation threshold and optimum processing fluence. We should also include the taper angle that can be expected for a particular material and fluence, and the minimum practical feature size achievable with focusing optics commonly used for machining purposes.

3. CLASSIFICATION OF MATERIALS

There are four classes of materials that are commonly laser micromachined: metals, ceramics, plastics, glasses. We will now give a general overview of the results one can expect from machining the different classes of materials with the three classes of lasers discussed above. There will, of course, be considerable differences between materials within classes. We will also look at how to determine which laser is appropriate for a particular application. Generally speaking the considerations are feature quality, desired feature size, and processing speed, i.e. cost.

3.1 Metals

Metals require a high energy density to ablate. For some, as mentioned above, the energy densities produced by the RF CO_2 laser are too low to be effective. The Nd:YLF laser will ablate most, if not all metals. However, since the Nd:YLF is a fairly low average power laser compared to the CO_2 , the processing speeds for the Nd:YLF are much lower than those of the CO_2 when it is effective. The low average power also limits the thickness of the metal that the Nd:YLF can practically cut to about 40 mil, whereas a 150 Watt RF CO_2 laser can cut metals up to about 100 mil thick. Micromachining metals with the CO_2 laser results in dross on the exit side of the cut or hole. This is resolidified molten material which has been blown through the cut by the assist gas and has adhered to the bottom surface. Processing with the Nd:YLF laser does not result in dross because material is completely vaporized.

Like the Nd:YLF laser the excimer is capable of micromachining most, if not all metals, but again requires a high energy density or fluence. The high energy of the ultra-violet photons couple very strongly to the material and the penetration depth per pulse is shallow allowing for precise material removal. Also, since practically all the laser energy goes into material removal, there is very little thermal energy translated into the surrounding area. The excimer laser, therefore, produces a small heat affected zone (HAZ), and the quality of features produced is very good, i.e. clean walls, sharp corners, little debris or recast material, and little microcracking. The combination of the short light wavelength and mask imaging technique allows one to achieve high resolution and feature sizes to less than 10 microns. However the quality of extremely

small features in metals is not as good as it is in plastics because the material removal mechanism is more thermal in nature resulting in distortion of features less than about 5 microns. This is also somewhat thickness dependent. For example, it is difficult to achieve a round 3 micron hole in, say, 200 micron thick material, but it is considerably easier to produce a 5 micron hole in 25 micron thick material. The cost of higher quality and the ability to produce smaller features is processing speed. Of the lasers we will refer to in this paper the excimer produces the highest quality, and smallest feature size, and has the slowest processing speeds.

In choosing a laser for a metal micromachining application it is important to consider several things. Since cost is almost always an important issue and, since the CO₂ laser processes faster than either the Nd:YLF or the excimer, it is usually the first laser to consider using. If the CO₂ can produce a small enough feature of high enough quality, then it is the laser of choice. However, one must remember a few things: the smallest practical feature size is about 50 microns, there will always be some heat affected zone, and there will be dross on the laser exit side of the processed material. If the CO₂ is ruled out for one of the reasons just mentioned, or if the material requires a higher power density than the CO₂ can generate then the next laser to consider is a Q-switched solid state laser. A Nd:YLF laser is typically 10 times faster than an excimer laser, but up to 100 times slower than a CO₂. If an application requires a very small feature with a tight tolerance of highest possible quality and smallest heat affected zone than one must choose the excimer laser. An example would be a 10 or 20 μm hole with a tolerance of $\pm 1\mu\text{m}$ in a thin metal film, say 25 or 50 μm thick, where any surface slag or dross would be unacceptable.

3.2 Ceramics

Ceramics, in many ways, have nearly identical processing characteristics too those of metals, however, they exhibit less recast material. They require approximately the same energy densities as metals and the achievable feature size and quality is about the same. Also, as with metals, there are some ceramics that do not machine well with the CO₂ because the particular composition requires a very high power density. For these ceramics a Q-switched solid state laser may be required. The same factors as those discussed above come into play when selecting a laser for a ceramic application. Also because ceramics are more susceptible to fracturing from heat stress than metals, the proximity of features is sometimes a consideration. Both the CO₂ and Nd:YLF generate more heat and microcracking than the excimer, so if one requires, for example, an array of very closely packed holes the excimer may be necessary to prevent the fracturing from one hole to the next.²

3.3 Glass

Glasses have different absorption characteristics than either ceramics or metals. Some, such as Silica, are transmitting at the Nd:YLF wavelength (1.047 μm) and the excimer wavelength (248 nm) but are absorbing at the CO₂ wavelength. Therefore, the absorption spectrum is often the primary consideration in laser selection. The CO₂ processing speed of glass is usually quite a bit slower than for metals or ceramics because one must often use caution not to induce cracking. On occasion it has been found beneficial to heat a glass to a temperature close to its annealing point to improve machineability. In cases where the glass is absorbing at an ultra-violet wavelength the quality gained by using the excimer is not as great as it is with materials such as ceramics or plastics. For example, there is often chipping on feature edges. Therefore it is often desirable to use the CO₂ laser if the required hole or cut is not too small. That is, the quality gained by using the excimer may not be worth the cost in processing speed.

3.4 Plastics

Plastics require a low energy density to machine compared to the other classes of materials discussed above. Machining them is therefore practical with either the CO₂ or excimer laser, and which laser is selected is determined almost entirely by the size and feature quality needed. The quality achievable with the excimer laser is extremely good in the case of plastics: very small heat affected zone, little debris, high resolution, and feature sizes down to 1 or 2 microns. The performance of the CO₂ laser is inferior with respect to all these areas, but it is typically 100 to 1000 times faster. Also the CO₂ very effectively vaporizes plastics and there is no recast material to worry about. This allows machining through very thick materials to be possible, because it is not necessary to use a gas assist to remove molten material. It is possible, for example, to drill small, 8 to 10 mil holes through half inch thick Teflon®.

4. PROCESSING TECHNIQUES

In this section we will briefly review the different processing techniques employed when micromachining with the lasers discussed above. There is, of course, considerable variation in details depending on the specific application.

The CO₂ and solid state lasers are used in focal point machining where usually a single element lens is used to focus the beam to the smallest possible spot size. Spot diameters are typically 2 to 10 mil. The exact spot size depends largely on four things: the wavelength of the laser (λ), the focal length of the lens (f), the mode characteristic of the laser beam which is commonly quantified by the M^2 specification, and the diameter of the beam entering the focusing lens (D). The diameter of a focused spot is approximately $1.22 M^2 \lambda / D$. Different spot sizes are achieved by using different focal length lenses and by possibly expanding the beam diameter. Increasing or decreasing the spot size has the obvious effect of changing the size of machined features, holes or kerfs, but it also affects the energy density which is inversely proportional the area of the spot. Therefore, one can not make the machining spot arbitrarily large to produce whatever size hole is desired. Typically a spot size is chosen which will produce at least the minimum energy density required for a material, and then holes of larger size are cut out either by revolving the piece being machined around the beam or by trepanning the beam itself in a circular fashion. As stated above the CO₂ laser usually requires an assist gas. This is a flow of gas, usually dry, filtered air, through a nozzle coaxial with the beam. The gas assist serves to remove molten material from the kerf, keep the focusing optic clean, and in some cases enhance processing speed.

The excimer laser mask imaging technique was discussed in some detail above. Here the shape of the feature is the same as that of the mask, so it can be a circle, square, number, letter, or whatever is desired. The size of the image is that of the mask divided by the demagnification. The demagnification is the ratio of the distance from the mask to the focusing lens (o - for object) to the distance from the lens to the image (i - for image), governed by $1/f = 1/o + 1/i$ where f is the lens focal length. Typical focusing lenses are singlets and doublets from 50 to 500 mm in focal length. The energy density, or fluence, at the work piece is proportional to the square of the demagnification. The starting point for determining an optical set up is therefore knowing what energy density, or fluence, is required for the application and then calculating a demagnification based on the fluence through the mask. One then selects the size of the mask based on the size of the feature desired. With plastics a very low fluence is required for ablation and therefore a relatively low demagnification can be used. This means that in general larger features can be imaged in plastics than in metals, ceramics, or glass.

Another common excimer processing technique employs a contact mask. Here the mask is the exact same size and shape of the desired feature and is placed directly on the work surface. The excimer laser beam is often focused along just one axis using a cylindrical lens to produce the necessary fluence, and then the part and contact mask are scanned under the beam. Contact masks are usually used in low fluence applications where the beam will not ablate the mask itself.

5. PARAMETERS

We will now present sample data sets of different processing parameters for various materials and the different lasers discussed above.

5.1 excimer

As already mentioned the most relevant parameter for excimer processing is the etch rate per pulse. It is not very meaningful to discuss processing speed in a general sense since this is very much a function of how much of the actual beam is used for processing which varies greatly from one application to the next. It is important to know how etch rate varies with fluence since fluence is a quantity that, in principle, does not depend on beam utilization. Figure 1 is a graph of etch rate vs. fluence for alumina. The data was taken with an excimer laser operating at 248 nm. From the plot we see that the ablation threshold for alumina is about 4 J/cm². The etch rate then increases with fluence in a sublinear manner through the maximum fluence plotted. The etch rate for most ceramics saturates between 20 and 40 J/cm² at maximum etch rates between 0.1 and 0.2 microns per pulse.³ Figure 2 contains similar plots for glass, silicon rubber, and polycarbonate. The threshold for glass is similar to that of alumina while the other two soft materials have thresholds below 1 J/cm². Also the maximum etch rates approach 10 times that of alumina.

Figure 3 contains plots of etch rate vs. depth in three materials: silicon rubber at 13 J/cm², glass at 13 J/cm², and polycarbonate at 4.4 J/cm². The etch rate clearly decreases for all three but most severely for the hard material, glass; less so for silicon rubber, and even less for polycarbonate.

5.2 CO₂ and Nd:YLF

Since these two lasers are largely used for cutting and drilling we will present sample tabulated data of achievable cutting and drilling speeds and the associated parameters. Figure 4 is a table of cutting parameters taken with the 150 watt Coherent Diamond® RF excited pulsed CO₂ laser. One should keep in mind that not in all cases is the maximum possible cutting rate indicated. For example silica and sapphire machine with very similar characteristics, but the entry for sapphire

indicates a pulse width of only 20 μsec whereas that for silica is 300 μsec and, in turn, the speed for the silica entry is much greater. As mentioned above the exact parameters used are often dictated by the particular application. So if it is necessary to take precaution not to overheat and stress a material then usually a very short pulse width is required. Figure 5 is a similar table of hole drilling times and parameters.

Figures 6 and 7 are tables of cutting and drilling parameters for the Nd:YLF laser operating at the fundamental wavelength. Notice the approximately two orders of magnitude increase in processing speed of the CO_2 compared to the solid state laser. This is why we usually say that if the CO_2 can possibly do it, then it is most likely the laser of choice.

We are also collecting data from a frequency doubled Nd:YLF laser, which functions in much the same way as the fundamental Nd:YLF laser, but is more suitable for processing some materials due to their high absorption in the visible portion of the spectrum. Two examples of such materials are zinc selenide and copper. Figure 8 is a graph of etch depth vs. number of pulses per mil of cut taken while making 0.1 inch long cuts in the two materials. The laser was focused to a 4 mil spot with a 150 mm doublet lens and operated at 1 khz. The plots indicate that the etch rate remains constant at least to about 500 microns in zinc selenide and 100 microns in copper. From the plots we determine the etch rates to be about 0.019 microns per pulse per inch of cut at 7 watt in zinc selenide and 0.025 microns per pulse per inch in copper.

Etch rate vs. Fluence in alumina

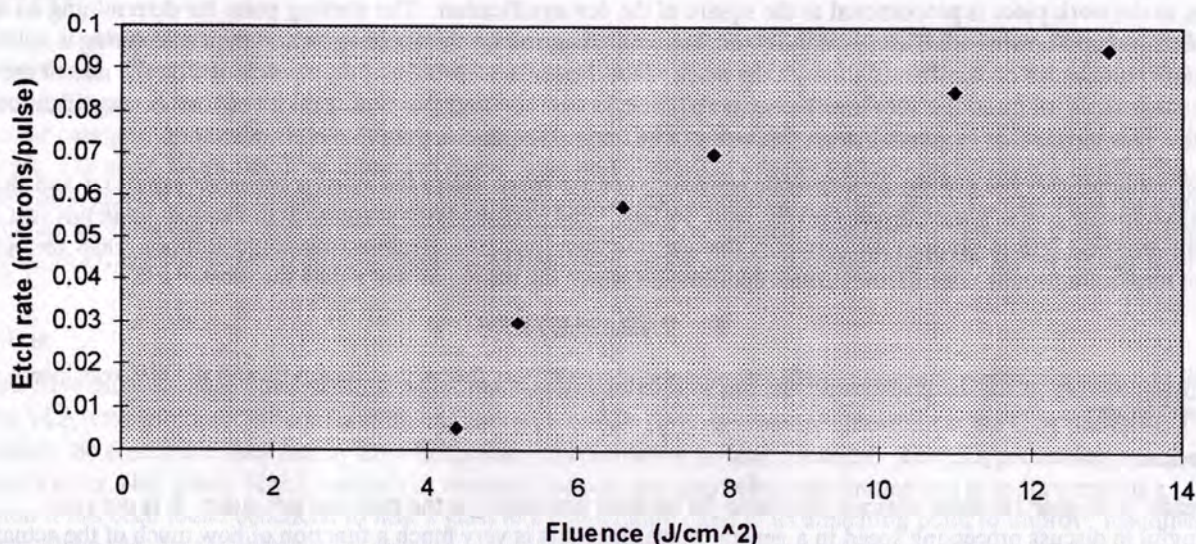


fig. 1

Etch rate in microns per pulse vs. fluence in J/cm^2 in alumina using excimer laser operating at 248 nm.

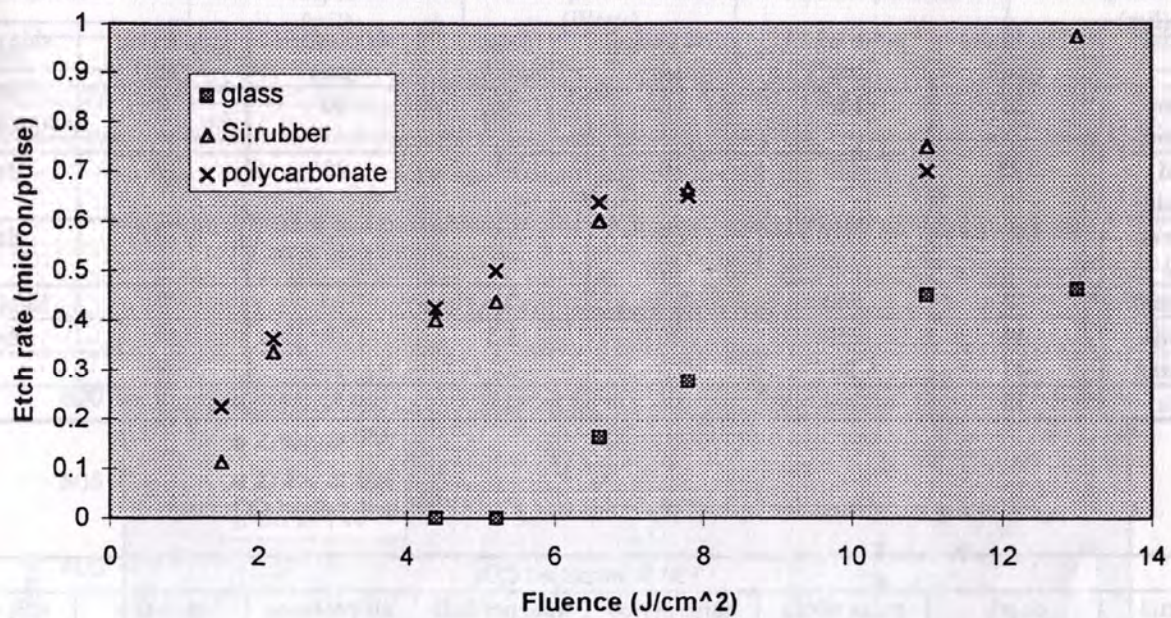


fig. 2

Etch rate vs. fluence in silicon rubber, glass, and polycarbonate using excimer laser at 248 nm.

Etch rate vs. depth

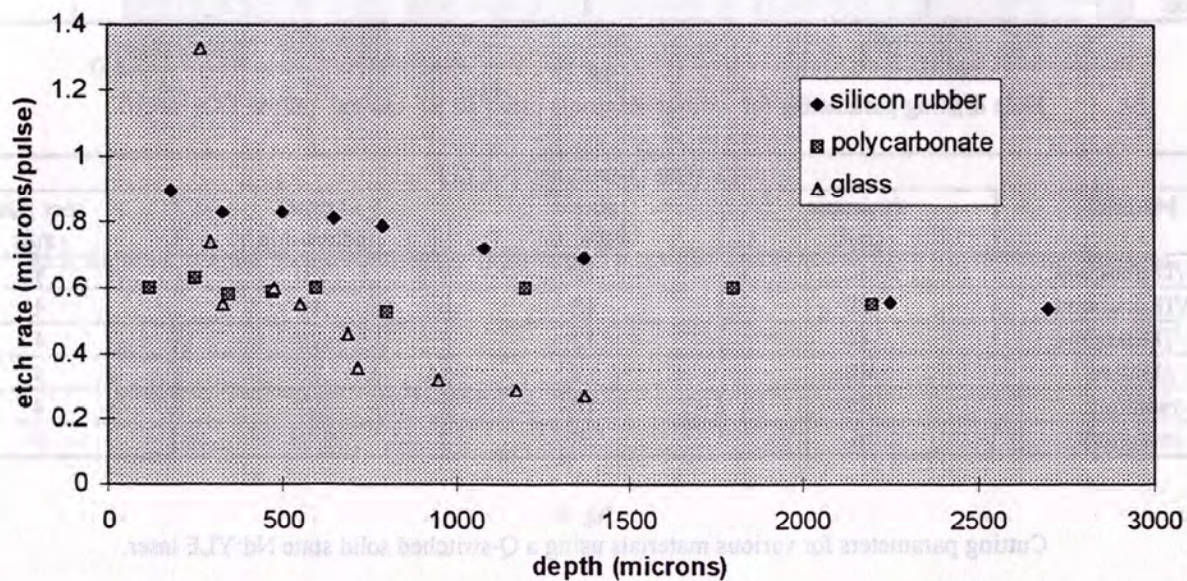


fig. 3

Etch rate in microns per pulse vs. depth in microns. Data taken through hole drilling in silicon rubber (13 J/cm²), glass (13 J/cm²), and polycarbonate (4.4 J/cm²).

150 Watt pulsed CO ₂							
Material	Thickness (mil)	pulse width (μsec.)	pulse period (msec.)	speed (inch/min.)	air pressure (psi)	spot size (mil)	side effects
green ceramic	10	100	4.0	60	10	7	
fired ceramic	125	400	2.0	6.0	40	7	dross
stainless steel	62	400	1.0	15	80	7	dross
germanium	12	500	3.0	22	20	7	light dross
alumina	40	250	8.0	3.5	70	7	dross
sapphire	40	20	2.0	.02	10	7	
silica	38	300	2.5	15	50	7	

fig. 4
Cutting parameters for various materials using an RF excited pulsed CO₂ laser.

150 Watt pulsed CO ₂							
Material	depth (mil)	pulse width (μsec.)	pulse period (msec.)	time per hole (seconds)	air pressure (psi)	spot size (mil)	side effects
Teflon™	125	24	5.0	25		7	
Teflon™	125	40	60	36		4.5	
Plexiglas™	500	500	40	10		7	
alumina	40	250	1.0	.05	70	7	dross
stainless steel	20	250	1.0	.01	50	4.5	dross

fig. 5
Hole drilling parameters for various materials using an RF excited pulsed CO₂ laser.

12 Watt Q-switched Nd:YLF				
Material	thickness (mil)	power (Watts)	speed (inches/min.)	spot size (mil)
CVD diamond	10	12	1.0	4
CVD diamond	20	12	.45	4
CVD diamond	40	12	.20	4
alumina	40	12	.16	4
tantalum	20	10	.62	4
tantalum	5	12	2.75	4

fig. 6
Cutting parameters for various materials using a Q-switched solid state Nd:YLF laser.

12 Watt Q-switched Nd:YLF				
Material	depth (mil)	power (Watts)	seconds per hole	spot size (mil)
tantalum	20	10	1.0	4
alumina	54	10	3.0	4
CVD diamond	18	10	2.5	4

fig. 7

Hole drilling parameters for various material using a Q- switched solid state Nd:YLF laser.

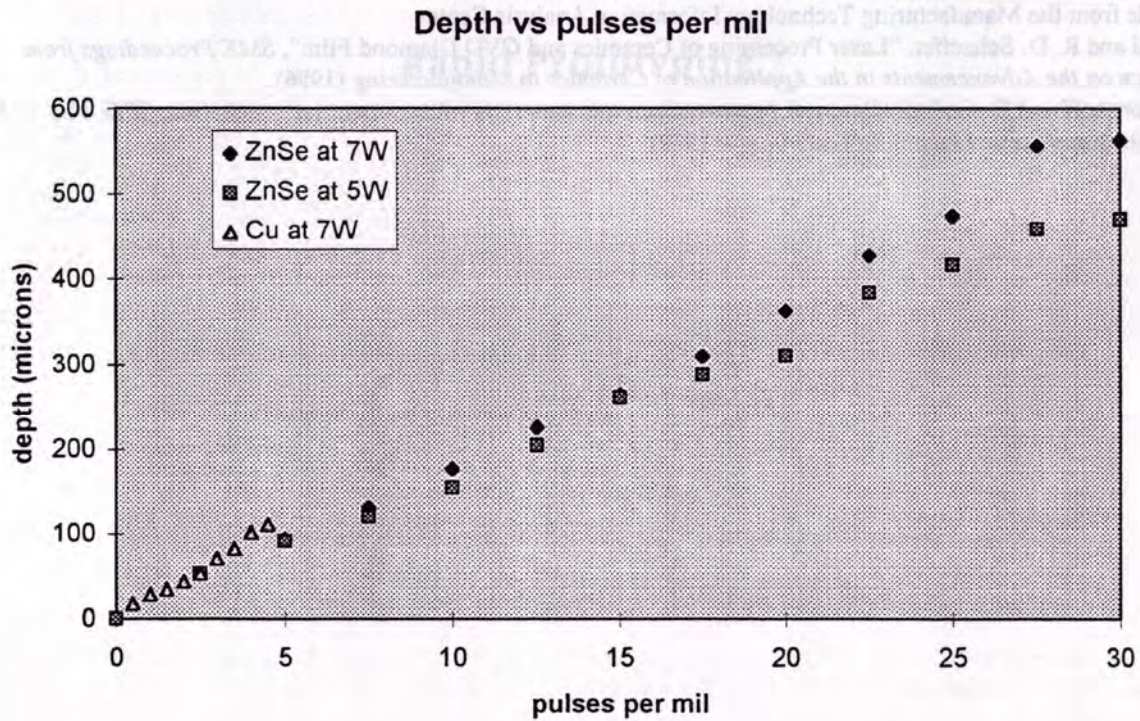


fig. 8

Etch depth vs. number of laser pulses per mil travel. Data was taken from cutting a 0.1 inch long segment.

6. CONCLUSION

The data on laser micromachining processing parameters which has been accumulating for the last several years is now being sorted and cataloged for easier access by those who work every day in laser micromachining as well as those who have an occasional application. The lasers we are concentrating effort on are the excimer, pulsed CO₂, Q-switched solid state, and any others in the future that can expand the capabilities of lasers in micromachining. We have relied so far on data accumulated in our own facility, but we welcome any interested partner to contact the authors of this paper. Also information regarding processing and parameters can be found on our Web page (<http://www.Resonetics.Com>)

ACKNOWLEDGEMENTS

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¹ Available from the Manufacturing Technology Information Analysis Center

² J. Angell and R. D. Schaeffer, "Laser Processing of Ceramics and CVD Diamond Film", *SME Proceedings from Conference on the Advancements in the Application of Ceramics in Manufacturing* (1996)

³ H. K. Tönshoff and O. Gedrat, "Removal process of ceramic materials with excimer laser radiation, *SPIE Vol. 1132 High Power Lasers and Laser Machining Technology* (1989)

Material	Thickness (mm)	Power (W)	Spot Size (mm)	Speed (mm/min)
Teflon™	0.1	10	0.5	100
Teflon™	0.2	10	0.5	100
Picodias™	0.1	10	0.5	100
stainless	0.1	10	0.5	100
stainless	0.2	10	0.5	100
steel	0.1	10	0.5	100

Material	Thickness (mm)	Power (W)	Spot Size (mm)	Speed (mm/min)
CVD diamond	20	12	0.5	100
CVD diamond	40	12	0.5	100
stainless	40	12	0.5	100
stainless	20	10	0.5	100
stainless	5	12	0.5	100

Fig. 4
Cutting parameters for various materials using a Q-switched solid state Nd:YLF laser