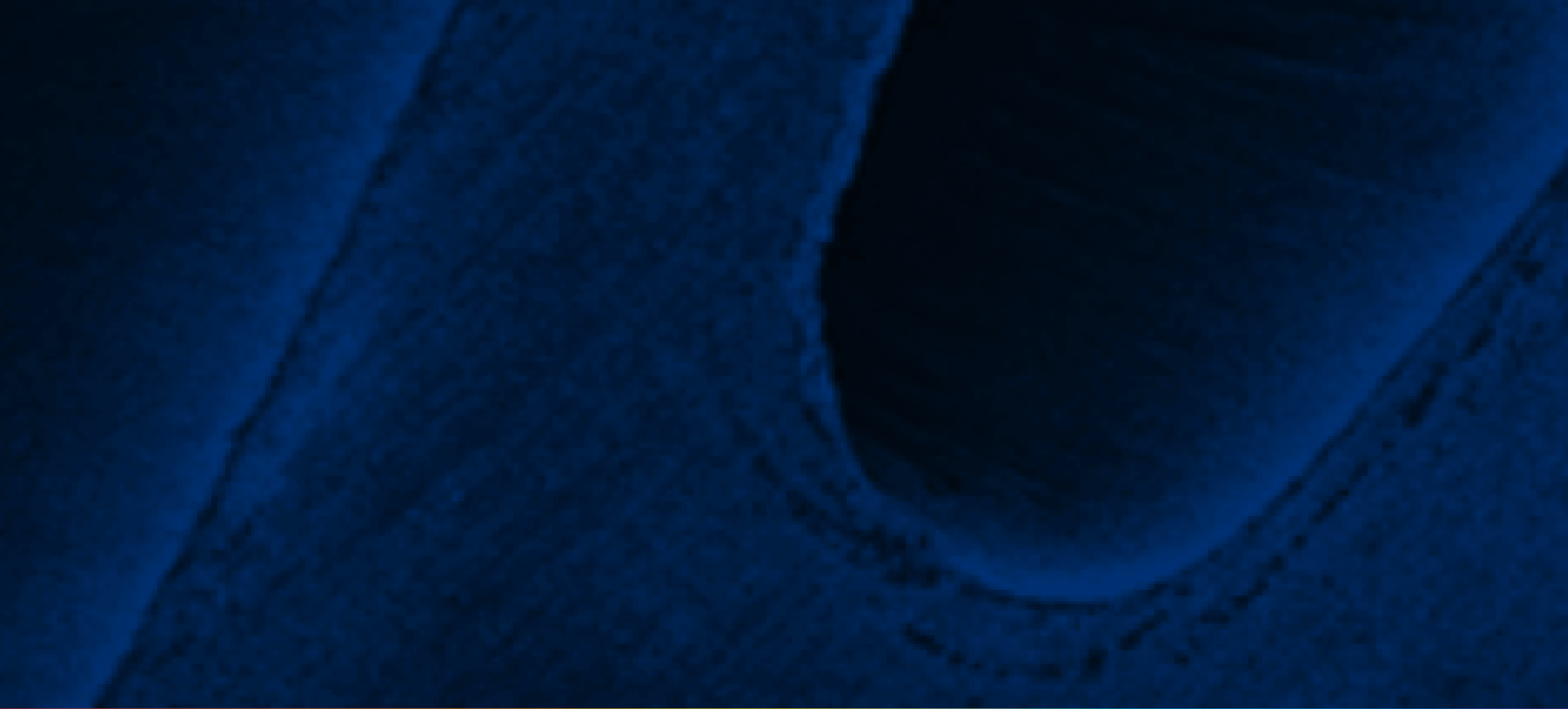

Ultrafast Laser Micromachining Handbook

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Contents

Introduction

Machining materials with lasers – a technology first introduced in the early 1970's – is now used routinely in many industries. Laser micromachining is a more recent development. First demonstrated in the 1980's, micromachining with lasers is an evolving technology. Initially laser micromachining was based on continuous wave or long-pulse lasers. With these "conventional" lasers, the heat transferred from the laser beam to the work piece introduced numerous restrictions that limit the precision and the quality of the machining process. In other words, laser micromachining is... well, not so micro, but rather course by some of today's standards. Machinists have learned ways to minimize the negative effects associated with heat transfer through various types of pre- and post-processing. These additional steps considerably increase the complexity and cost of the machining operation.

Note that heat-diffusion is not limited to laser machining. Tool bits deposit mechanical energy into the material that is being machined, a portion of which is converted to heat. This heat energy does not stay localized where it was initially deposited. It moves away in a characteristic time - the so-called "heat-diffusion time." This is a familiar phenomenon. If you turn on the heating element on an electric stove, it will take a few seconds to warm up. The same happens at the microscopic level, but the time scales involved are quite different. The typical "heat-diffusion time" encountered in laser machining is not counted in seconds, but rather in picoseconds (a picosecond is a millionth of a millionth of a second).

In the early nineties, scientists at the University of Michigan discovered that the transfer of heat from the laser beam to the work piece could be defeated using ultrafast laser pulses instead of standard long-pulse lasers. Essentially machining with laser pulses of very short duration eliminates heat flow to surrounding materials. This discovery opened the way for fine laser micromachining.

Before looking in detail at some samples that were machined with ultrafast pulses, let's first take a closer look at the way lasers interact with matter. To make this complex science reasonably understandable, we have simplified or ignored many issues: we arbitrarily divide the physics of how light interacts with materials into two time regimes - one in which the laser pulse is either very, very short (called ultrafast or ultrashort), and another in which the laser pulse is not so short (which we call "long"). Ultrafast, or ultrashort, means that the laser pulse has a duration that is somewhat less than about 10 picoseconds - usually some fraction of a picosecond (femtosecond). "Long" means that the pulse is longer than about 10 picoseconds, that is, longer than the heat-diffusion time. These long pulse lasers may be continuous, quasi-continuous, or Q-switched, but in any case they are generating long pulses compared to the heat-diffusion time.

2.0 Machining with Ultrafast Lasers

The reasons why lasers that produce very short pulses of light (called either ultrafast or ultrashort pulse lasers) generally produce high quality micromachining results can be traced to the mechanisms by which these pulses interact with matter.

Ultrafast pulses of light interact with matter in a manner that is totally different from the way traditional laser pulses interact with materials! Why this happens will be explained in more detail in the following sections, but for now it is important that you let go of the belief that what we are about to describe to you is simply the same micromachining process done on a different time scale.

For now, we can summarize the conclusion by saying that micromachining quality is a strong function of the amount of heat deposited in the work piece, or more exactly, a function of the amount of heat that is left behind in the material that can and does cause damage. Ultrafast pulses are extremely short by any standard. So short that the energy they deposit in material does not have time to leak away from the micromachining spot via mechanisms like thermal conduction. So much energy is deposited in the material so fast that the material is forced into a state of matter that physicists call a plasma. This plasma then expands away from the material as a highly energetic gas, taking almost all the heat away with it. Essentially, the material goes from a solid to a gas phase without first going through a melt phase. Consequently, very little heat is left behind to damage the material. This means that the machining quality is high.

No other kind of machining can create this very highly energetic state of matter. In part it is the unique ability of ultrafast lasers to create this state that is the reason why they produce results so different from those produced by traditional lasers used to machine materials.

But there are other advantages.

A more detailed explanation…

The intent of the following presentation is to give you a detailed understanding of the processes involved in traditional laser machining, so that you can better understand how ultrafast laser machining differs from traditional machining techniques.

We should begin by saying that these are complex – which is a physicist's way of saying that some things are not yet fully understood. In spite of this, however, we do know that the very short optical pulses interact with matter in a manner that is totally different from other types of machining, including conventional laser machining. We know, for example, that the interaction of ultrashort laser pulses with matter is highly reproducible (for reasons that will be discussed in Chapter 9). This makes for high quality micromachining with very reproducible results, shot-after-shot.

To make this complex science reasonably understandable, we have simplified or ignored many issues. Should you be interested in a more in-depth reading on the subject, please contact us and we will be happy to provide you with a reference list of relevant research papers.

3.0 Machining with Long Pulses

For the sake of this discussion, we arbitrarily divide the physics of how light interacts with materials into two time regimes – one in which the laser pulse is either very, very short (called ultrafast or ultrashort) and another in which the laser pulse is not so short (which we call 'long'). Ultrafast or ultrashort means that the laser pulse has a duration that is somewhat less than about 10 picoseconds – usually some fraction of a picosecond. 'Long' means that the pulse is longer than about 10 picoseconds. These long pulse lasers may be continuous, quasi-continuous, or Q-switched, but in any case they are all generating long pulses by the unusual standards we use here.

Note that almost all the commercial lasers used in industrial settings today fall in the "long pulse" laser category. Let's first take a look at what happens when material is machined with these long pulse lasers.

The most fundamental feature of material interaction in the long pulse regime is that the heat deposited by the laser in the material diffuses away during the pulse duration, as shown in Figure 3.1. Technically speaking, the laser pulse duration is longer than the heat diffusion time. This may be desirable if you are doing laser welding, but for most micromachining jobs, heat diffusion into the surrounding material is undesirable. Why? There are several reasons why heat diffusion is detrimental to the quality of the machining.

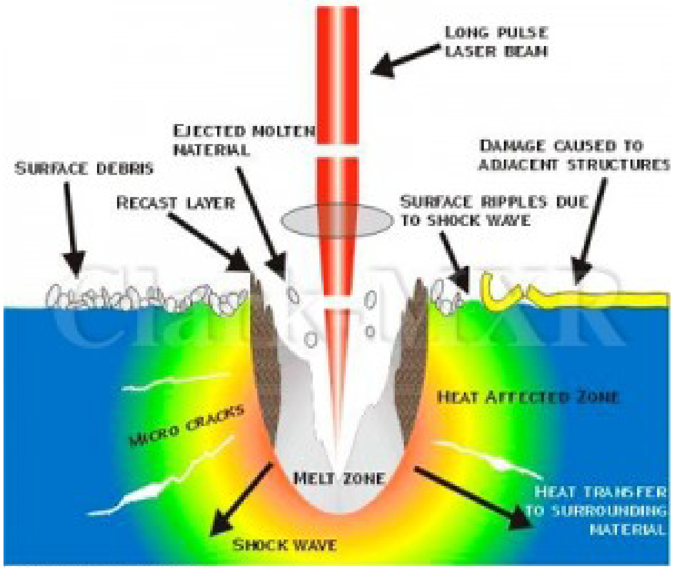


Figure 3.1: Long-Pulse Laser Matter Interaction.

Heat diffusion reduces the efficiency of the micromachining process. Heat diffusion sucks energy away from the work spot – energy that would otherwise go into removing material. Think of it as trying to fill a bucket full of holes with water. You have to pour a lot more water into the bucket to compensate for the water that leaks away. The higher the heat conductivity of the material the bigger the size of the holes and the more water you need to be poured into the bucket to fill it.

Figure 3.1 highlights the numerous physical phenomena that are present when machining with a long laser pulse. These effects are best observed in the animated version of Figure 3.1. The absorption of the long laser pulse leads to melting and then sputter evaporation of the material which can contaminate the surrounding area, produce micro-cracks, and remove material over dimensions much larger than the spot. Other adverse effects are damage to adjacent structures, delamination, formation of recast material, and poor shot-to-shot reproducibility.

Heat-diffusion also reduces the temperature at the focal spot (the machining spot), clamping the working temperature not much above the melting point of the material. Material is removed by depositing a lot of energy into the melted material which boils. As shown in Figure 3.1, this boiling ejects globs of the molten material away from the work zone. The ejected globs form drops that fall back onto the surface and contaminate the sample. These droplets can be rather large. They retain a fair amount of residual heat and may bind strongly to the sample. Removal of these contaminants may be difficult or impossible without damaging the target.

Heat-diffusion also reduces the accuracy of the micromachining operation. Typically, heat diffuses away from the focal spot (and there is plenty of heat because the process is inefficient!) and melts an area that is much larger than the laser spot size. It is therefore difficult to do very fine machining. In other words, the boiling that results in material removal is not limited to the spot size of the beam itself. Thus, while the minimum laser spot size might be in the range of one micron or less, in many materials it is not possible to create features with dimensions much smaller than 10 microns diameter.

Heat-diffusion affects a large zone around the machining spot. This zone is referred to as the “heat-affected zone” or HAZ. The heating (and subsequent cooling) waves that propagate through the HAZ causes mechanical stress and can create microcracks (or in some cases macrocracks) in the surrounding material (see Figure 3.1). These defects are ‘frozen’ in the structure when the material cools. In subsequent routine use, these cracks may propagate deep into the bulk of the material and cause premature device failure. A closely associated phenomena is the formation of a recast layer of material around the hole. This resolidified material often has a physical and/or chemical structure that is very different from the unmelted material. This recast layer may be mechanically weaker and must often be removed. In some applications, for example arterial stent manufacturing, this recast layer (also called ‘slag’) is removed through extensive and expensive post-process cleaning before the device can be used inside the human body.

Heat-diffusion is sometimes associated with the formation of surface shock waves. These shock waves can damage nearby device structures or delaminate multilayer materials. While the amplitude of the shock waves varies with the material being processed, it is generally true that the more energy deposited in the micromachining process the stronger the associated shock waves.

Clearly, heat diffusion is associated with numerous phenomena that affect the micromachining process. Reducing, or better, eliminating, heat diffusion is therefore desirable. We will get back to this in Chapter 5.

There are other limitations associated with laser machining. For example traditional lasers cannot readily machine transparent materials. That is not too surprising!

But ultrafast lasers can! Yes, as surprising as this may sound, ultrafast lasers can machine transparent material. We will review this in Chapter 13.

To summarize, in the case of micromachining with conventional long pulse lasers (or more conventional machining tools), heat-diffusion dominates the micromachining process. This introduces numerous undesirable side effects that reduces the value of the machining.

4.0 Long Pulse Machining Example

NVAR, an alloy formed of Nickel and Iron, has an extremely small coefficient of thermal expansion at room temperature. INVAR is often called for in the design of machinery that must be extremely stable. This sample was machined using a "long" pulse laser. The laser pulse parameters are: pulse duration 8 ns, energy 0.5 mJ. The machining was not assisted by an air jet.

It is quite obvious that the machining process under these conditions is not very clean. A recast layer can be clearly seen near the edges of the channel. Large debris are also seen in the vicinity of the cut. Note that one could have used some type of an air jet to assist in the machining process. The air jet function would be to physically project the melt phase away from the work zone. This would have resulted in a cleaner-looking cut, but also would have contaminated the sample down-stream.

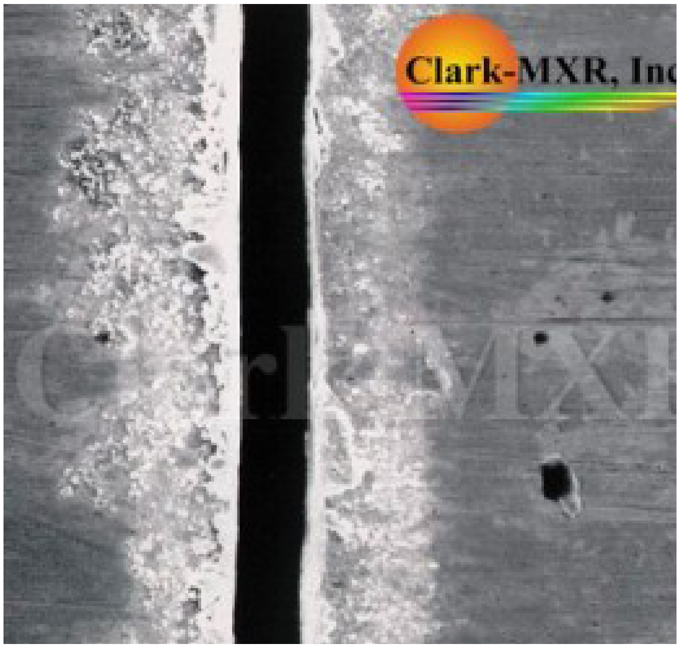


Figure 4.1: A channel made in 1mm thick INVAR (nickel/iron alloy) with long (nanosecond) pulses.

5.0 Machining with Ultrafast Laser Pulses

This chapter is concerned with the ablation of matter with ultrafast laser pulses. The most fundamental feature of laser-matter interaction in the very fast pulse regime is that the heat deposited by the laser into the material does not have time to move away from the work spot during the time the laser pulse is illuminating the material. The duration of the laser pulse is shorter than the heat diffusion time. This is a very unusual and very desirable regime, which can be reached only with ultrafast lasers.

This regime has numerous advantages as illustrated in the Figure 5.1 below.

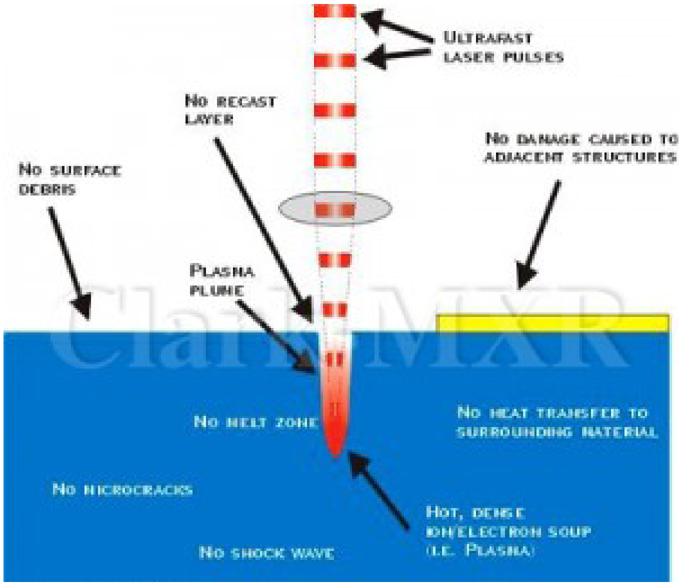


Figure 5.1: Ultrafast-Pulse Laser-Matter Interaction.

You will notice that this figure is much simpler than Figure 3.1, and there is a good reason for this. Physical processes like heat conduction, etc. don't have time to leach energy away from the process of plasma formation and subsequent material ejection.

Because the energy does not have the time to diffuse away, the efficiency of the machining process is high. If you remember the analogy we made in Chapter 3, this is similar to filling a bucket with no holes! The laser energy has nowhere to go (or more precisely does not have the time to move away). It just piles up at the level of the working spot, whose temperature rises instantly past the melting point of the material and goes, very quickly, well beyond even the evaporation point. In fact, the temperature keeps on climbing into what is called the plasma regime. This may seem strange. It is certainly not a common experience. How can this happen?

Femtosecond lasers, like our model CPA-2101, deliver an incredible amount of peak power. These systems routinely deliver 5 to 10 Gigawatts of peak power (this is more than the average power delivered by a large nuclear plant).The laser intensity easily reaches the hundreds of Terawatts per square centimeter range at the work spot. Absolutely, positively nothing else that is man-made gets anywhere close to this power density.

No materials can withstand the forces at work at these power densities. This means that with ultrafast laser pulses we can machine very hard materials, as well as materials with extremely high melting points such as Molybdenum, Rhenium, etc.

What else does this lack of thermal diffusion do to the machining process?

After the ultrafast laser pulse creates the plasma in the surface of the material, the pressures created by the forces within it cause the material to expand outward from the surface in a highly energetic plume or gas. The internal forces that previously held the material together are vastly insufficient to contain this expansion of highly ionized atoms (physicists call these charged atoms "ions") and electrons from the surface. Because the electrons are lighter and more energetic than the ions, they come off the material first, followed later by the ions. And because the ions all have some positive charge, they repel each other as they expand away from the material. Consequently, there are no droplets that condense onto the surrounding material. Additionally, since there is no melt phase, there is no splattering of material onto the surrounding surface.

Micromachining with femtosecond pulses offer some additional advantages as shown in subsequent chapters.

6.0 Ultrafast Laser Machining Example

A channel machined in 1 mm thick INVAR, Nickel/Iron alloy under the same experimental conditions as the long pulse channel in Figure 4.1, but with ultrafast pulses. This channel was machined with 200 femtosecond pulses, 0.5 mJ energy per pulse. It is quite obvious that the channel machined with femtosecond pulses is cleaner than the sample machined with nanosecond pulses. Note also the absence of a recast layer. It is also clear that the machining process was more efficient – the channel is larger. The edges are straighter. Overall the quality of the micromachining is much higher.

Figure 6.1: A channel made in 1mm thick INVAR (nickel/iron alloy) with ultrafast (femtosecond, on left) pulses and long (nanosecond, on right) pulses.

7.0 Contamination and Debris

This sheet of INVAR was micromachined with a long-pulse laser. It should be compared with the following picture, where the same material was machined with an ultrafast laser. The sample is heavily contaminated. We tried, unsuccessfully, to clean this sample with a mild jet of dry nitrogen.

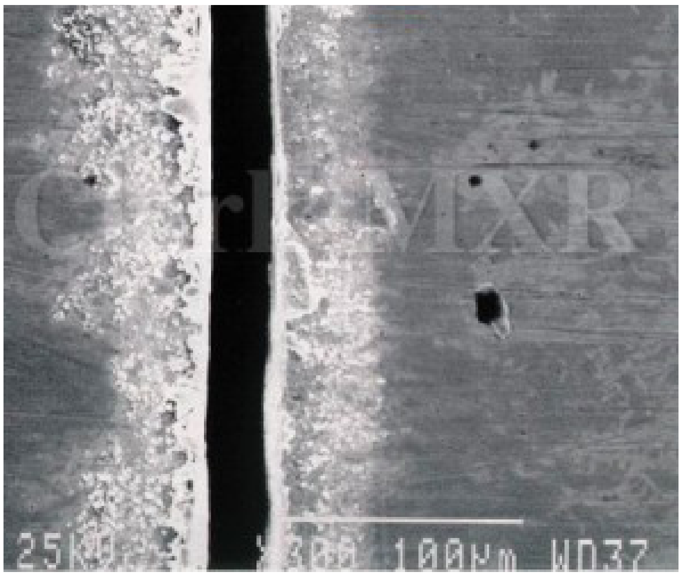


Figure 7.1: A slot machined in INVAR with nanosecond pulses.

Figure 7.2: Invar sheet machined with an ultrafast laser.

This sheet of INVAR was micromachined with a Clark-MXR ultrafast workstation. It should be compared with the previous picture, where the same material was machined with a long-pulse (10 nsec) laser. The femtosecond-processed sample was cleaned with a mild jet of dry nitrogen (just like the nanosecond-processed sample).

In conventional, (i.e. long-pulse), laser machining, large amounts of debris are created during the machining process. The debris, whose form depends on the material being machined, can be very difficult to remove.

In conventional machining, a large heat affected zone completely surrounds the work area. A heavy recast layer is present immediately along the edges of the slot. Outside the recast layer, an extended zone of debris (droplets of molten metal) is visible. This debris was still extremely hot when it landed on the surface. Removing this material will require substantial post processing efforts, if it can be done at all without damaging the surface. The situation is quite different when working with femtosecond lasers, as shown below.

With the ultrafast pulses very little debris was generated during the micromachining process, and what remains is not in the form of hot droplets that attached to the surface. Rather, the femtosecond process creates a fine dust that does not carry much heat, and therefore does not bind to the surface.

It should be noted that techniques have been developed to reduce the amount of debris created when machining with long-pulse lasers. Using powerful gas jets one can considerably reduce the amount of debris created, or one can push the debris far away from the work zone before re-deposition. A significant amount of work has gone in this debris mitigating effort. Users have developed jets with various geometries. Various gases have been used, including pure oxygen for rapid burn of the debris, etc.

These approaches can, in some cases, almost totally eliminate contamination of the sample by debris. (This of course does not alleviate the other problems associated with heat diffusion as encountered in long-pulse machining.)

8.0 Heat Affected Zone (HAZ)

The machining process with ultrashort (femtosecond) pulses of light (i.e. changing hard solid matter into an expanding plasma), is so rapid that there is little time for heat to diffuse away from the focal spot.

Heating of the surrounding area is significantly reduced and consequently all the negatives associated with a heat-affected zone are no longer present. No melt zone. No microcracks. No shock wave that can delaminate multilayer materials. No stress that can damage adjacent structures, and no recast layer.

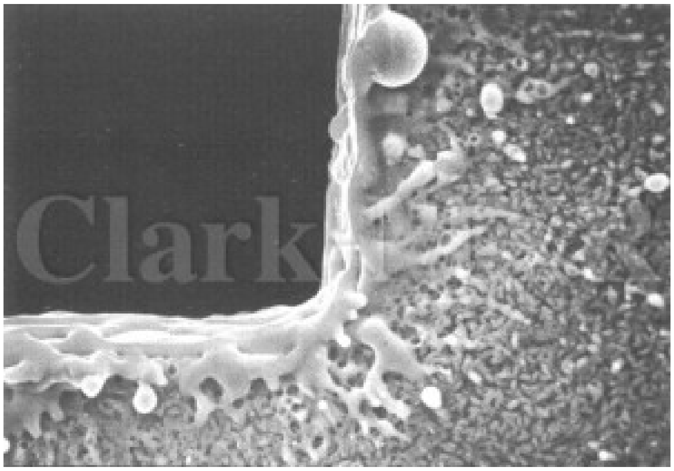


Figure 8.1: Slag formed in the heat affected zone (HAZ) during a long-pulse micromachining process.

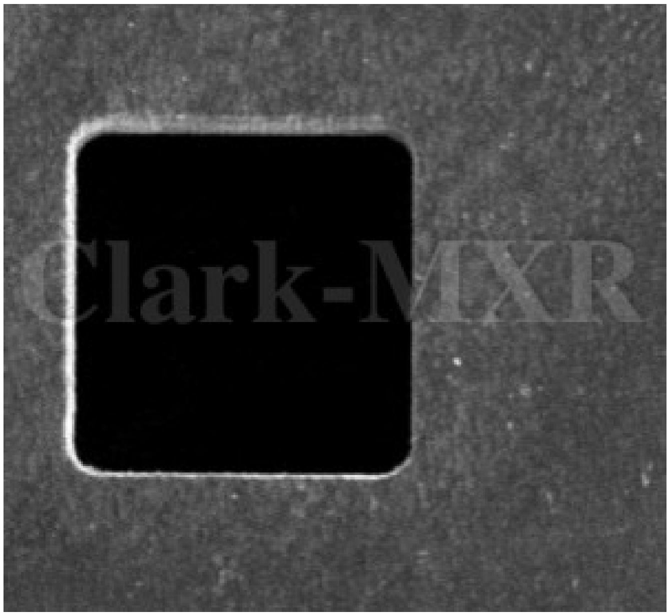


Figure 8.2: Absence of slag and HAZ during an ultrashort-pulse micromachinng process.

9.0 Machining Accuracy

Limiting Factors Affecting the Efficiency of the Micromachining Process

While most of the unique characteristics associated with micromachining with ultrafast lasers can be explained by the lack of thermal diffusion, some important features, notably the extreme high shot-to-shot repeatability, the ability to create sub-micron features, and the capability to machine inside transparent materials, requires a more detailed look at the physics behind the interaction of light with matter.

How does light interact with matter? The following links will help us get a deeper understanding.

HEAT DIFFUSION

Heat Diffusion can severely reduce the accuracy of the micromachining operation. With conventional lasers, heat diffuses away from the focal spot and melts an area that is much larger than the laser spot size. It is therefore difficult to do very fine machining. In other words, the boiling that results in material removal is not limited to the spot size of the beam itself. Thus, while the minimum laser spot size might be in the range of one micron or less, in many materials it is not possible to create features with dimensions much smaller than 10 to 30 microns.

When machining with ultrafast laser pulses, heat diffusion is virtually eliminated. This effect does not affect the ultimate accuracy of the machining process.

OPTICAL WAVELENGTH

A second factor limiting the machining accuracy is the laser operating wavelength and/or the beam focusing optics.

The best focal spot is proportional to the wavelength divided by the numerical aperture (NA) of the focusing objective. Note that this observation would indicate that shorter wavelengths are always better than longer wavelengths. While this is theoretically correct, it is important to realize that most often heat diffusion imposes limitations that are much more restrictive than those dictated by wavelength and NA considerations.

POSITIONING OF THE LASER BEAM WITH RESPECT TO THE WORK PIECE

Machining accuracy is also limited by the operator's ability to precisely position the laser beam with respect to the workpiece. There are three approaches here: 1) leave the beam fixed and move the workpiece using translations stages, 2) leave the workpiece stationary and move the laser beam using galvanometers, or 3) move stages and beam. Ultrafast workstations can be equipped with various translation stages, galvanometers and beam steering robotics thereby offering trade-offs between laser processing requirements such as resolution, speed and cost.

STOCHASTIC OR DETERMINISTIC NATURE OF THE ABLATION PROCESS

While most of the unique characteristics associated with micromachining with ultrafast lasers can be explained by the lack of thermal diffusion, some important features, notably the extreme high shot-to-shot repeatability, the ability to create sub-micron features, and the capability to machine inside transparent materials, requires a more detailed look at the physics behind the interaction of light with matter. How does light interact with matter? Figures 9.1, and 9.2 will help us get a deeper understanding.

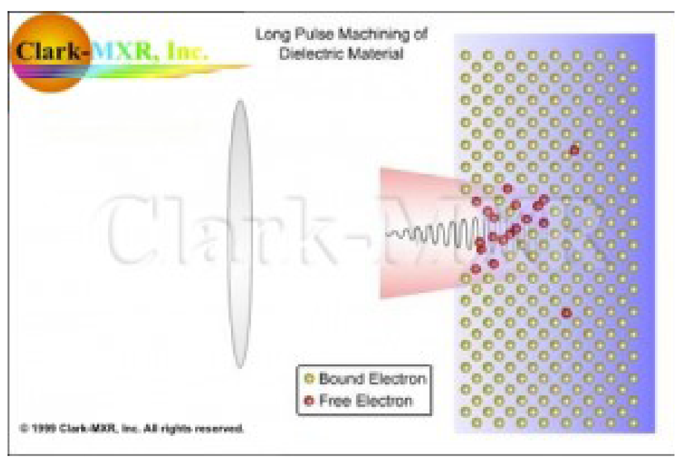


Figure 9.1: Avalanche Ionization – This figure shows a long laser pulse interacting with a typical sample. The sample is formed of atoms and electrons. For clarity Figure 9.1 shows only the

electrons. The electrons are either "bound" or "free". Bound electrons are tightly attached to the local atoms. In contrast free electrons are not tightly attached to the local atoms. The ratio of bound electrons to free electrons is a function of the material. Metals have mostly free electrons, while semiconductors and insulators have very few free electrons. The figure shows very few free electrons. It is representative of a semiconductor. Click here to view an animation of the process.

Now lets look at the other key component present in the animations viewed through Figure 9.1: the laser pulse. So far we have represented laser pulses as a "solid chunk of energy." Now we need to think of the optical pulse as an electromagnetic wave packet. The wave frequency corresponds to the "color" of the laser pulse, the length of the wave packet corresponds to the duration of the laser pulse, and the amplitude of the wave corresponds to the peak power of the laser.

As the optical wave packet (i.e. laser pulse) enters the sample the electrons start to oscillate. The bound electrons are tightly localized and can only "wiggle" slightly. In contrast, the free electrons, which are unbound, can oscillate strongly once they are in the laser field. While oscillating they occasionally collide with the surrounding atoms. If the laser field is intense enough, a free electron colliding with a surrounding atom will knock off an additional electron. Now there are two free electrons that are being driven by the light field. They in turn can knock two more electrons off atoms in the surrounding material. These four electrons create four more free electrons through collisions, and so on.

This type of multiplication effect is called an avalanche effect, and because it creates electrons by ionizing atoms, it is called 'avalanche ionization.'

The full process is shown in the animations as seen through Figure 9.1. For this avalanche process to start, a free electron must be present initially in the electromagnetic field. The absence of free electrons prevents the avalanche process from significantly starting and ultimately hinders the material ablation.

In metal there are plenty of free electrons; the avalanche process starts immediately. This leads to reproducible machining (there may be other problems associated with heat diffusion).

In semiconductors or isolators there are naturally very few free electrons. The avalanche process may start right away or may not, depending on the presence or absence of a free electron in the beam path. If we have initially several free electrons in the electromagnetic field, then the process will be very "efficient". If we have no free electron, then the process will not start. We are basically relying on luck to get the machining process going! This variability, which is inherent to the physical process, leads to unstable machining rates. Note that the laser may be perfectly stable, the beam spot size and amount of energy in the pulse may be precisely the same from shot-to-shot, yet the material ablation will vary significantly from shot to shot. This is a serious limitation when trying to do very fine machining.

Can we do anything about it? Can we outsmart the physics of the interaction?

Yes, that is possible. If we can somehow create, a priori, large quantities of free electrons then the presence or absence of naturally occurring free electrons will no longer be an important factor. What matters is the total number of free electrons, not their origin.

So, how do we produce a large quantity of free electrons?

There are at least two ways to do it. Both approaches rely on the same underlying principle: We always have a lot of electrons in our work piece. It is just that the vast majority of them may be bound and not useful to get the avalanche process going. If we could turn these bound electrons immediately into free electrons then we would have solved our problem.

We can achieve this goal using lasers working in the ultraviolet, or using ultrafast lasers. Figure 9.2 shows what happens with an ultrafast laser.

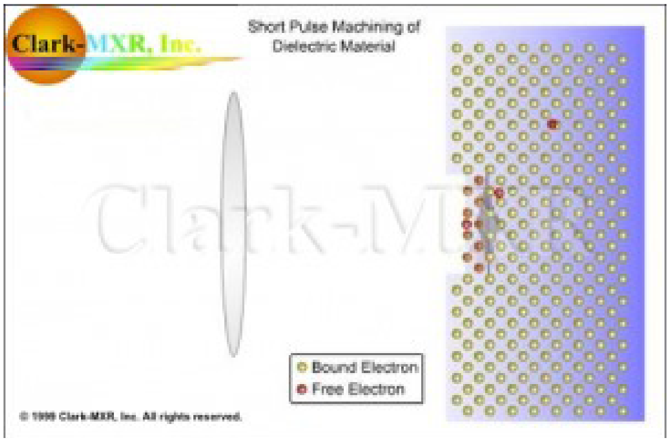


Figure 9.2: Avalanche Ionization – This figure shows the same material as Figure 9.1 but the ablation is with ultrashort pulses of light.

The amplitude of the electromagnetic field corresponds to the peak power of the laser. Ultrafast lasers generate tremendous peak power as shown in Figure 9.2.

Remember what we said earlier: "...as the optical wave packet (i.e. laser pulse) enters the sample, the electrons start to oscillate. The bound electrons are tightly localized and can only "wiggle" slightly." This is correct under normal conditions. But we are not operating under "normal" conditions when the sample is illuminated with ultrafast pulses and their extremely intense electromagnetic fields.

The electromagnetic field is so high that the "bound" electrons are knocked free. Immediately we find ourselves with a large quantity of free electrons and the avalanche ionization process can start immediately, reliably, and reproducibly. This leads to high-quality machining, as shown clearly in Figure 9.3.

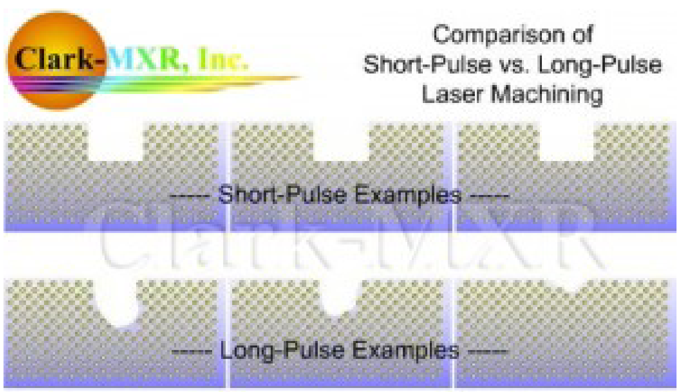


Figure 9.3: Avalanche Ionization – This figures shows a comparison between long and short pulsed lasers.

10.0 Sub-Micron Features

The unique combination of multiphoton absorption and saturated avalanche ionization provided by ultrafast laser pulses that makes it possible to machine materials on dimensions much smaller than 1 micron.

Let's now use this high-reproducibility concept to create sub-micron features in materials.

If your objective is to create the smallest feature you can possibly make by machining with light, you must focus that light on the smallest spot you can possibly make. The size of the spot is determined by several factors, but for our purposes we limit this discussion to making the statement that the smallest spot that you can get is about the same as the wavelength of the light you are using to make it. Thus, if the wavelength of light is about 0.5 microns, then the smallest spot you can create is about 0.5 microns. However, as noted above, while both ultrafast pulse lasers and long pulse lasers can both operate at wavelengths of 0.5 microns, the long pulse laser is not capable of creating a machined feature that is much less than about 10 microns because of heat diffusion into the surrounding material.

Referring to Figure 10-1, below, we can see how an ultrafast laser pulse can create features substantially below that of the central wavelength of the laser pulse itself. First, we focus the ultrafast laser on a spot with a profile which has a peak intensity in the center of the beam and smoothly decreases radially outward from the center (a "Gaussian" spot). Remember we said earlier that machining with ultrafast laser pulses is a threshold process? If we adjust the intensity of the laser spot on the surface of the material (which is a very easy thing to do) so that just the peak of the beam is above threshold, then we will remove material only in that very limited area! That very limited area can be as little as one-tenth the size of the spot itself.

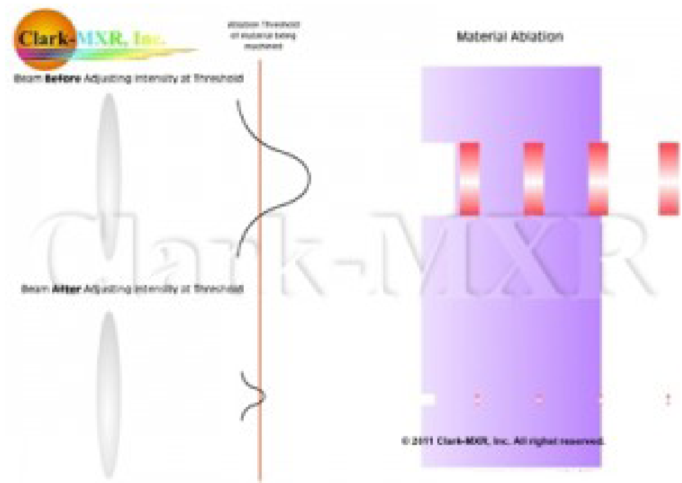


Figure 10.1: Creating sub-micron features.

Now imagine that we generate ultrafast laser pulses that have a central wavelength of 0.2 microns. Using ultrafast pulses of light we should be able to create features as small as 0.02 microns, or 20 nanometers.

It is important to note that it is the unique combination of multiphoton absorption and saturated avalanche ionization provided by ultrafast laser pulses that makes it possible to machine materials on dimensions much smaller than 1 micron. Without this unique characteristic of machining with ultrafast laser pulses and the highly deterministic nature of the process, it would not be possible to achieve these results without a heat-affected zone. More specifically, it is not possible to get comparable highly repeatable sub-micron machining with long pulse laser systems.

11.0 Machining Inside Bulk Material

With respect to machining inside bulk materials, if you have gotten this far, then you have all the tools needed to understand this process.

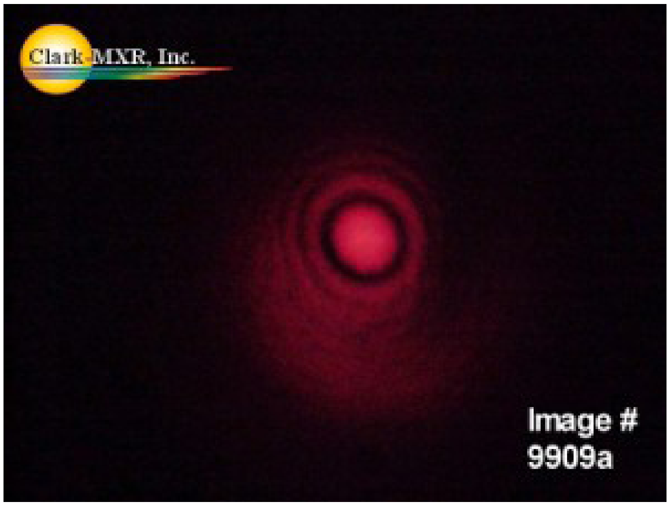
As we all know, some materials are transparent at some wavelengths of light. Glass, for example, is transparent for all wavelengths of light in the visible. That is, it does not absorb visible light – provided the intensity stays below the threshold for multiphoton absorption. We can exceed that threshold by focusing ultrafast laser pulses to a spot inside the materials.

When the intensity exceeds the threshold for plasma formation, very localized absorption does occur at the focal point spot. Once again, this plasma expands. But this time it is confined by the surrounding material. The effect of the expansion is to create a void within a very dense shell of material – a pit within the glass itself. This process is not limited to glass. Pits can be created in any material by focusing an ultrafast laser pulse inside the material, whether it is amorphous or crystalline.

12.0 Introduction to Waveguides

You can manufacture single mode waveguides in materials with femtosecond lasers. At 775 nm, glass is transparent to incident light. Our micromachining technology uses ultrafast laser pulses to locally melt the glass via confined multiphoton absorption and avalanche ionization inside the bulk material. The glass then resolidifies, changing its physical properties. The result is an index gradient that acts like a waveguide. A beam of light propagating along the same path in the glass will be guided in the same manner as an index-guided fiber guides light inside it.

Only ultrafast lasers are capable of producing this effect in transparent materials. With longer pulse lasers (nanoseconds), the sample damages before the intensity reaches the threshold at which guides are formed. The picture below shows the output of a waveguide made in glass on a far-field screen using a HeNe laser. The waveguide can be made either single mode or multimode.



The image below is an artist's rendering of the waveguide concepts described above.

Note: Color was added to the waveguide for illustrative purposes only. In reality, scattering losses are extremely low and the beam is NOT visible while propagating inside the waveguide.

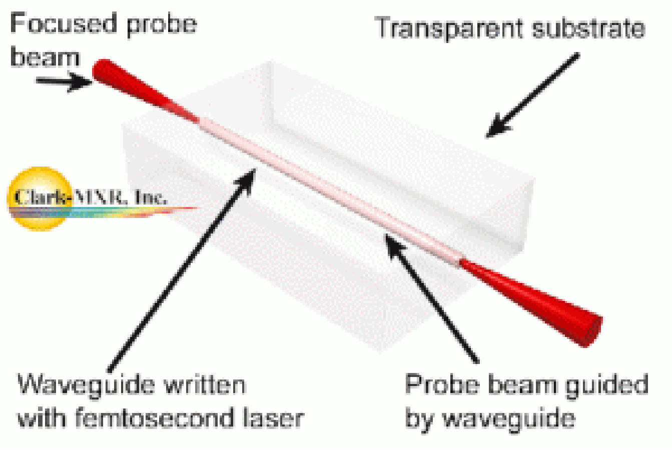


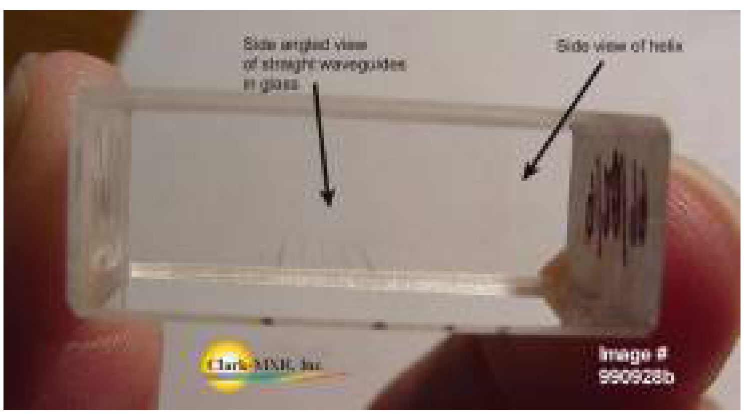
Photo Gallery: Explore the possibilities of using ultrafast lasers to manufacture 3D features in the bulk of transparent materials.

All the images below show samples of linear and 3D features that were written in our micromachining job shop using the Clark-MXR, Inc. femtosecond direct write source.

Note: All images were taken with a digital camera and have not been re-touched.


Clark-MXR, Inc.
Large diameter helix
Small diameter helix
Image # 990927c


Clark-MXR, Inc.
Top View
Helix in Glass
Image # 990928a


Side angled view of straight waveguides in glass
Side view of helix
Clark-MXR, Inc.
Image # 990928b


Clark-MXR, Inc.
Image # 990927d


Image # 990927e

13.0 Active Waveguides

The photosensitivity of silica fibers in the UV region of the spectrum was discovered more than 20 years ago [1] and has proved to be a key point in the advancement of guided wave devices. Using UV light in a simple holographic setup [2] one can write gratings in planar waveguides and optical fibers or can even write directly waveguides in bulk glasses [3]. However, this method has inherent limitations since many glasses are not sufficiently sensitive to yield a large enough index of refraction change, and also the UV photosensitivity range is very close to the absorption edge of most glasses.

Mourou and co-workers have proposed that femtosecond laser pulses can be used to induce localized refractive index increase in a wide variety of glasses. Thermally stable optical waveguides were produced [4] in silicate, borosilicate, chalcogenide and fluoride glasses and, also, more complex structures such as a Y-junction splitter [5] and long period gratings [6] have been reported.

We report for the first time, to the best of our knowledge, an active waveguide device directly written using near-IR femtosecond laser pulses. The device is a waveguide amplifier in a Nd-doped silicate glass.

Experimental Details and Discussion:

The material used in this study was a commercially available Nd-doped silicate glass rod. From the measured absorption coefficient of the glass we estimate the Nd doping level to be around 2 x 1020 ions/cm3.

For waveguide fabrication, a Clark-MXR femtosecond workstation operating at 775-nm was used. From throughput measurements of waveguides of lengths varying between 2mm and 10mm we estimate the waveguide propagation losses to be well below 0.5dB/cm. Gain measurements were performed using an Argon-ion pump laser as a source at 514-nm and a signal at 1054-nm provided by a continuous-wave laser. The data on the gain of the amplifier at a signal of 1054-nm is presented in Figure 13.1. (The gain was measured as the ratio between the signal power with the pump turned on and the signal power with the pump turned off.)

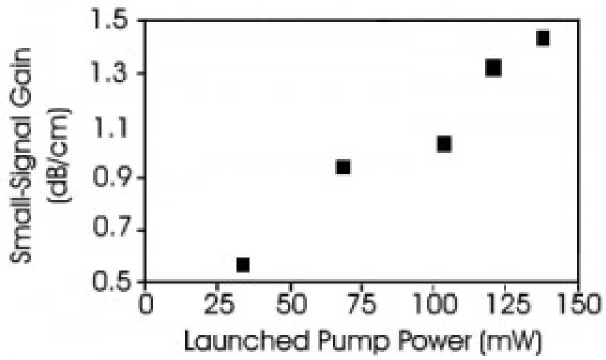


Figure 13.1: Small signal gain versus launched pump power

Fluorescence data indicate that the emission cross-section at 1054-nm is only half as large as that at the 1062-nm the peak. Thus this device should provide a peak unsaturated gain of about 3dB/cm for launched pump power levels of about 140 mW.

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14.0 Shortcomings of Femtosecond Lasers

Like all new technologies, femtosecond lasers still have some shortcomings when compared with other micromachining techniques.

Until recently, low throughput due to low average power was the dominant prohibitive factor in establishing the use of femtosecond lasers for commercial applications. Then, along came our IMPULSE source, whose > 20 W average power beam has dramatically increased throughput capabilities, and has subsequently lowered the cost of femtosecond micromachining on a per-unit basis to a more acceptable level for production. Additional increases in average output power are on the horizon at Clark-MXR. Look for new increases in throughput and new production capabilities in the near future.

15.0 Materials We've Machined

Below is a list of some of the materials we have micromachined:

CERAMICS

Alumina

Silicon Nitride

Thermal Barrier Coating

DIELECTRICS

Diamond

Glass

Magnesium Fluoride (MgF2)

METALS

Chromium/Glass

Copper

Enamel

INVAR (Iron/Nickel Alloy)

N5 (Nickel-based Super Alloy)

Nickel/Polymide

Rhenium

Stainless Steel

Molybdenum

Platinum

Gold

Brass

Nitinol

SEMICONDUCTORS

Gallium Arsenide (GaAs)

Silicon

POLYMERS

Polydimethylsiloxane (PDMS)

Teflon

16.0 Conclusion

Ultrafast laser pulses can machine materials (and/or locally change their chemical or physical porperties) to produce no contamination to the surrounding material, no melt zone, no microcracks, no shock wave, no delamination, no recast layer, and do damage to adjacent structures. It is highly reproducible, it can be used to create sub-micron features, and it can machine features inside transparent materials. We continue to find new applications for this technology.

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Glossary

Ablation: The use of a laser to remove any material by vaporization.

Absorption: The loss of light as it passes through a material, generally due to its conversion to other energy forms (typically heat).

Avalanche Ionization: Free electrons colliding with a surrounding atoms, and breaking off more free electrons, create additional free electrons at an exponential rate.

Conductivity: A material property that is the inverse to its resistance to the flow of electricity.

Defects: Faults which cause the material to be unusable for it intended purpose.

Features: While we have yet to create features this small to date in materials, the principle has been demonstrated.

Free Electrons: Electrons in the outer orbit around the nucleolus of an atom, they can be moved out of orbit comparatively easily.

Gigawatt: Most large nuclear power plants produce Megawatts of average power. This is a lot more energy than an ultrafast laser can produce of average power – which is typically one watt. So it is not necessary to have one thousand nuclear power plants all connected to the ultrafast laser at the same time to operate these ultrafast lasers! In fact, most residential houses have enough electricity to run one. The difference comes from the fact that in a nuclear power plant, power is being delivered continuously, whereas in these ultrafast lasers power is being compressed into pulses that are less than a trillionth of a second in duration.

Heat-Affected Zone (HAZ): It should be noted that under some conditions these effects can be present. The process has a threshold. Below that threshold energy from the laser pulse may be absorbed into the material and converted to heat that will dissipate into the surrounding material. Since the beam profile typically does not have sharp edges, some energy in the beam may be below the threshold for ablation. How much gets into the surrounding material depends on the exact beam shape, its relation to the threshold for ablation and the repetition rate of the laser. Typically, however, some set of conditions can be chosen to minimize these effects. The price for this minimization may be through-put; i.e. how fast material can be removed from the target. In some cases this may be unacceptably slow.

Heat-diffusion time: All tool bits deposit mechanical energy into the material that is being machined, a portion of which is converted to heat energy. Lasers deposit optical energy into materials that they machine, some of which is also converted to heat energy. This heat energy does not stay localized where it was deposited initially. It moves away in a characteristic time – the so-called "heat diffusion time". This is a familiar phenomenon. If you turn on the heating element on an electric stove, it will take a few seconds to warm-up. The same happens at the microscopic level, but the time scales involved are quite different. The typical "heat-diffusion time" encountered in laser machining is not counted in seconds but rather in picoseconds.

Intensity: Flux per unit solid angle.

Ionized: The gain or loss of one or more electrons in an atom, which causes it to carry a negative or a positive charge.

Ions: An atom that has gained or lost one or more electrons, and as a result, carries a positive or a negative charge.

Plasma: A plasma is a fourth state of matter well known to physicists but not well known to the layman – the other three states of matter being solid, liquid and gas. A plasma is a loosely bound soup of highly charged atoms and electrons containing so much energy that the forces that hold the material together are obliterated. Ultrafast lasers can produce this state of matter because they pack so many particles of light called photons into so small a time interval that when they interact with the atoms in the surface of the material, they strip as many as 15 electrons off the atom. Physicists call this process multiphoton ionization.

Peak Power: The maximum power supplied by a laser pulse.

Picosecond: A fraction of a second (10^{-12}). Abbreviated as p.

Power Density: In laser beam welding or heat treating, the instantaneous laser beam power per unit area. This parameter is key in determining the fusion zone profile (area of base metal melted) on a work piece.

Recast Layer: Molten metal which forms a layer of debris on the surface of the material during picosecond machining.

Slag: The unwanted material that is removed from metal when it is heated to a liquid state.

Stent: A device placed in a body structure, such as a blood vessel or the gastrointestinal tract, to provide support and to keep the structure open.

Terawatt: A unit or power equal to one trillion watts.

Threshold: So far we have talked only about ablation of materials. There are other processes that are more generally defined as 'physical and/or chemical changes in the structure of materials' that have properties that are similar to those associated with ablation – but differing thresholds. For example, it is possible to locally change the index of refraction of materials at the focus of an ultrafast laser beam, inside the bulk of the material (see our section on waveguides). This can have very useful consequences for the creation of devices used in telecommunication networks.

Ultrafast: As it relates to micromachining, a laser capable of generating light pulses that last only a few femtosecond's time. This can be achieved by nonlinear filtering to increase bandwidth and compress the pulse or by passive modelocking or synchronous pumping in conjunction with pulse-shaping techniques.

Ultrashort: See "Ultrafast."

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