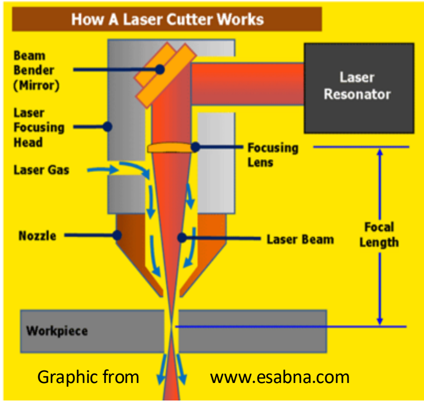
A Beginner's Guide to Laser Machining

In traditional machining, whether by scissor/guillotine, saw/file, or drill/mill, even abrasive paper!, the basic machining operation is that of shear failure,- ripping off some layers from those underlying. Shear is a mechanical force, so how can lasers machine,- when we learn in school that the photon rest mass is zero?

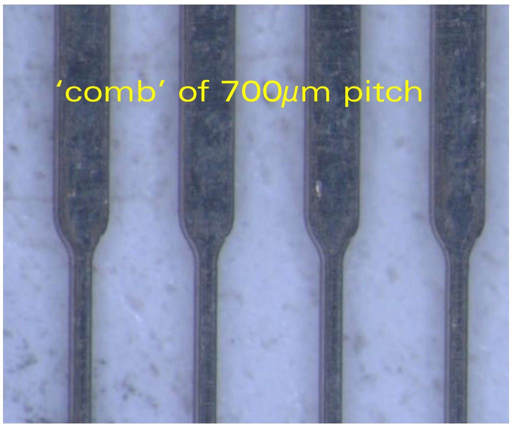
Melt Transition

In laser cutting/drilling of metals, the job of the laser to melt the metal. At the melting point the resistance to shear drops dramatically to zero (the main definition of the melt transition), and the actual ejection of the melt occurs either using a coaxial high-pressure gas jet (typical sheet metal cutting) or by pressure from surface vaporization (percussion drilling). For a melt-driven mechanism, depth control is difficult; most machining is through the entire thickness of the material.



Note that for this mechanism to work, the laser radiation must be efficiently absorbed by the material, which must have a more-or-less well-defined melt transition, whilst the laser emission characteristics have to be matched to the material and the machining dimensions.

Vaporisation & Short Pulses

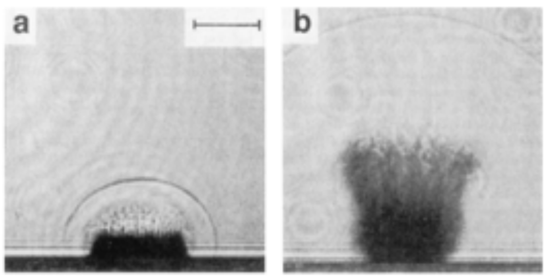


At higher power density, typically for short laser pulses, including excimer, machining may occur by surface vaporization, also for materials with no clear melt transition. This is an inherently slower process, since a smaller amount of material is removed at each step, from a thin layer. Therefore the ideal tool is a laser whose radiation is strongly absorbed in that thin layer, at high enough peak power density(i.e. short pulses), and with high repetition rate for efficient machining with low or non-existant HAZ. The new generation of ps/fs lasers with MHz rep. rates takes this to its logical conclusion; local peak power densities ensure efficient absorption even with material/wavelength combinations which would not do so at lesser power density; though note that one only gets ps machining quality if the beam is kept moving, otherwise thermal effects accumulate. Depth control is somewhat improved;

N.B. shallow depth machining can also be used for precision marking.

The Special Case of Polymers

In addition to machining by melting or vaporization, most polymers can also be finely micromachined by photo-ablative decomposition at wavelengths below about 300nm. For these short wavelengths, the large molecules typical of polymers are broken into smaller fragments by electronic excitation of the bonds. Since the smaller molecules have lower density, the irradiated volume expands rapidly, in fact so rapidly that the surface layers are ejected, at high velocity; Hans van Esdonk of ExciLas measured up to 32km/s! A characteristic of the process if that most of the excess energy is carried away in the form of kinetic energy by the ejected material, and therefore strangely enough the process is relatively cool,- an important point for thermally delicate materials. Depth control can be superb, to the order of $<1\mu m$, & capable of machining optical quality surfaces,but this process is not at all suited to removing large amounts of materiel.



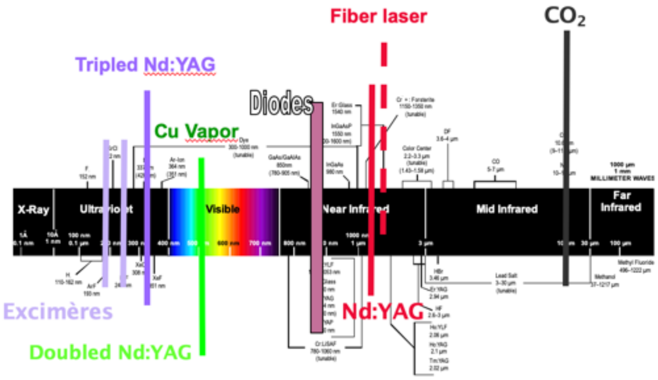
Some marking applications in polymers rely on thermal foaming of the material to generate contrast. This requires somewhat deeper absorption, at longer wavelength and longer pulse duration

Stress Cracking

We talk of cutting glass, but in most cases we mean ***breaking*** the glass in a controlled manner, by crack propagation using mechanical stress. In a similar way, brittle materials including glass can also be neatly cut without debris by crack propagation under thermally induced stress. To generate the stress, the laser beam must be adequately absorbed by the material over a considerable depth.

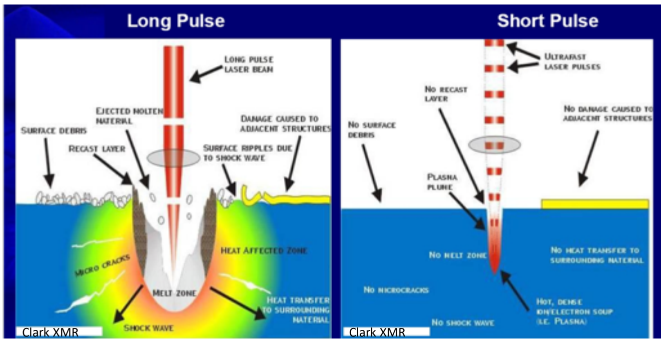
Wavelength

The most obvious point is that to have an efficient interaction with the material, the laser energy has to be absorbed, which mostly depends on wavelength; lasers in common use cover a much wider range than our tiny visual spectrum. (Qu. Why has evolution equipped us with eyes whose tissues are all transparent in the near IR, but the retina insensitive;- insects use these wavelengths, why not us? From a safety point of view, near-IR lasers are particularly dangerous to us since radiation can reach the sensitive retina in damaging quantities whilst we have no protective blink reflex)



Timescale

This excellent & oft-repeated graphic needs little additional comment.



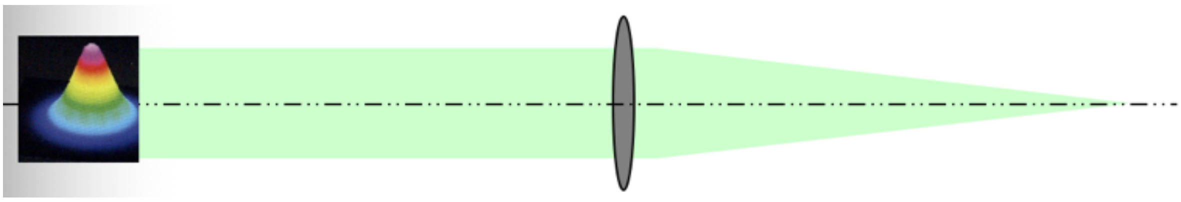
During a laser pulse of duration t, heat will travel distance on the order of sqrt($4\alpha t$) where α is the thermal diffusivity in cm^2/s, equal to $K/\rho C$, and mainly determined by the thermal conductivity K. Thus, machining of fine features in thermally conducting materials absolutely requires short pulse duration. For ps/fs lasers, the thermal diffusion distance can be $<1\mu m$.

If short enough, there can also be multiphoton effects which ensure efficient coupling of laser energy to materiel even if the latter would normally be transparent,- i.e. non absorbing,- at these wavelengths.

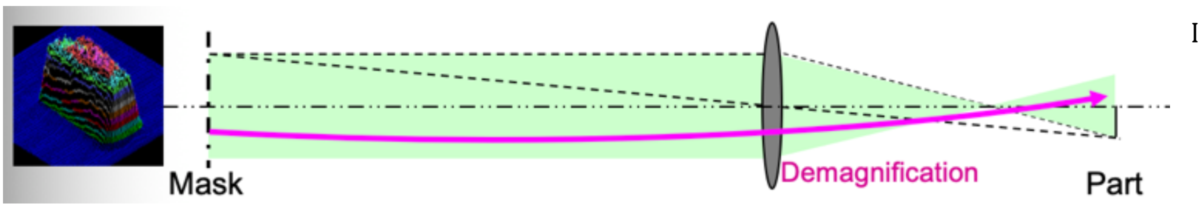
Technique

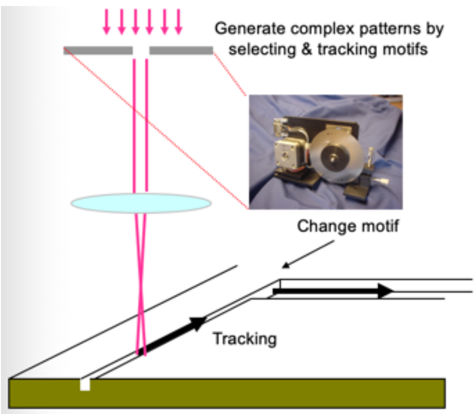
Sometimes more than one of these mechanisms operates, for e.g. Perspex (PMMA) can be cut readily using a CW CO2 laser(melting), and also micromachined using excimer lasers,- and sometimes the physics of what happens is intermediate. In any case, the machining precision will always ultimately be limited by wavelength dependent optical diffraction effects.

With gaussian beams, lasers are used a focal point tools, i.e. the focussed beam is tracked across the part to contour complex shapes(sequential method); this generally requires high rep. rate to perform in a reasonable time.



Sometimes the desired motif is generated by a mask, whose complete image is projected onto the part(parallel method).





In an intermediate case, smaller fundamental motifs are projected and combined with part motion to produce larger or more complex motifs,- a combination of sequential/parallel processing. The most efficient method in any particular task depends partly on the task, and partly on the characteristics of the laser source. As always, the tool & technique must be chosen for the job in hand.

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