Basic Guide to Laser Micromachining

In traditional machining, whether cutting by scissor/guillotine, saw/file, or drill/mill, the basic operation is shear failure. Shear is a mechanical force, so how can lasers machine, when the photon rest mass is zero?

Melt Transition

In traditional laser machining of metals, the job of the laser to melt the metal. At the melting point the resistance to shear drops dramatically to zero(one of the definitions of melting), and the actual ejection of the melt occurs either using a coaxial 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 material must have a more-or-less well-defined melt transition, the laser radiation must be efficiently absorbed by the material, whilst the laser emission characteristics have to be matched to the material and the machining dimensions. For e.g. during the 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 requires short pulse duration.

Vaporisation

At higher power density, typically for short laser pulses, 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. Shallow depth machining is used for 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 excitiation 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. A characteristic of the process if that much of the excess energy is carried away in the form of kinetic energy by the ejected material, and therefore the process is relatively cool,- an important point for thermally delicate materials.

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 consideable depth.

Summary

Sometimes more than one of these mechanisms operates, for e.g. Perspex can be cut readily using a CW CO2 laser(mechanism 1), and also micromachined using mechanism 3,- 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.

Sometimes, lasers are used a focal point tools, i.e. the focussed beam is tracked across the part to generate larger features(sequential method); this may require 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(par/sequ). The most efficient method in any particular task depends partly on the task, and partly on the characteristics of the laser source. The tool must be chosen for the job in hand.