# Fundamentals of Excimer Laser Micromachining

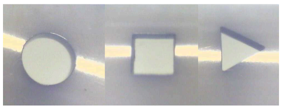
An excimer laser is highly multimodal, with standard optics has little coherence, emits a pulse of UV radiation from 10mJ to 1J (small & big lasers), in 5-30ns, and might much better be called a UV flashlight! The short wavelength means that incident energy is efficiently absorbed in the surface layers of all but a very few materials; the short pulse duration ensures high peak absorbed power densities, which can reach GW/cm2 or TW/cm3. Not surprisingly, the result is **ablation** of surface layers, either by **vaporisation**(metals/ceramics etc.) or **photo-ablative decomposition(**polymers), either constituting a 'machining' operation.

Depending on gas fill & optics, different wavelengths are available. 248nm (KrF transition) is the default choice, 193nm (ArF) can have somewhat higher precision and is mandatory for some materials which absorb weakly at 248nm, but has lower available energy, higher losses & requires a flushed beam path. XeCl(308nm) & XeF(351nm) have a few specialist applications. After **wavelength**, the main parameter is **energy density** (e.d.), typically in the range 0,25-25J/$cm^2$; machining takes place at rates are on the order of tenths of μm/shot, with reasonably good depth control according to the **shot dose.** Finally, **rep. rate** ,-limited to a few hundred Hz,- is rarely an important process parameter other than in terms of process speed or **throughpu**t.

Because of the poorly defined mode structure & far field beam profile, focal point applications are very rare; most processing is performed using projection optics, where the relatively large & uniform beam is used to illuminate a **mask**, whose demagnified image is then focussed on the part, with lateral definition which can be on the order of μm over areas of 1mm2 > 1cm2. We review below essential components & requirements of a **mask projection system for excimer laser micromachining.**

## Mask Types

The mask might define a **simple motif**,- e.g. circle, square, triangle, slit,- or a more **complex motif** which is then projected as a whole onto the part,- e.g. as lower right here. With simple motifs the final machining pattern on the part is built up from repetition of **selected motifs associated with part motion** in X,Y and laser firing; **machining depth** is mainly controlled by shot dose. Masks for simply-connected motifs may be made from laser cut or chemically etched shimstock; more precise or multiply-connected masks can be made using photoetching techniques on metal/quartz or dielectric blanks. Masks may be fixed, or hold a selection of simple motifs mounted on a motorized selector carousel,- or dynamic,- e.g. motorized slit or MRA(motorized rectangular aperture). Most masks define only clear areas in an opaque background but a few applications require soft-edged or grey scale masks;- the choice of mask type is determined by processing requirements.



## UV Illumination Optics

The role of the **illumination optics** is to match the laser o/p to the mask size/shape, to the useful aperture of the imaging lens, and to set the energy density; resulting e.d. on the part is multiplied by the square of **demag**(nification). Energy density is set to conform to a process window, or to accentuate/minimize some processing feature,- e.g. low/high taper. Illumination optics typically include **steering mirrors** & **energy controller,** and may include other elements such as **beam expanding telescope(BET) or beam concentrator, beam shaper** or **homogenizer, field lens** etc. Since the laser beam is not radially symmetric, illumination systems commonly include **anamorphic**(cylindrical) optics. The system builder has to understand these options & constraints.

Illumination optics design strives to use the beam efficiently (**BUF**=Beam Utilization Factor), and also has to take into account evolution of the beam profile over gas fill & cavity lifetime. Beam splitting may also be used to process parts in parallel.

## Image Projection Optics

Machining precision will be ultimately limited by the **optical resolution** of the imaging or **process lens**, as determined by useful **n.a.** (numerical aperture). Low cost **singlets** can be used at low n.a. or where the desired processing precision is such that aberrations can be tolerated, diffraction limited **multi-element lenses** of higher n.a. are optimized for the desired **demagnification**. Significant **working distance** is desirable to avoid damage by redeposit of ejecta, leading to focal lengths typically in the range 50-150mm. Generally the process lens is fixed to some kind of **focus mechanism** which may be motorized. If part alignment is to be performed it is desirable to be able to view the part through the lens(**TTL vision**), and lens performance at visible wavelengths must also be adequate for that task.

The complete assembly of illumination and projection optics is commonly referred to as a **BDU**(beam delivery unit)

## Part Handling

Parts for simple repetitive processing may be mounted on suitable **part fixture**. For more complex machining of flat parts a typical system includes X,Y stages, perhaps with vacuum chuck. Concepts such as positioning **resolution**, positioning

**repeatability** and **position accuracy** should be clearly understood and specified to suit the task; needless overspecification should be avoided. Position accuracy in a stacked system is determined not only by single axis drive precision, but by guiding accuracy(**straightness/flatness**), **orthogonality**, and in particular the effects of **roll**, **pitch** & **yaw** on a part which may be several cm above the plane(s) in which lie the guides.

Alignment of laser processing with existing features usually requires a **theta stage**, some applications require tilt stages, or the part to be rotated on a **mini-lathe**.

**Throughput optimization** will require consideration of **stage dynamics,** motion speeds, accelerations, settling times etc. Some processes are point to point, others require laser firing during part motion, so that **contour trajectory** is important. On large parts, synchronized motion of part and mask may be required using **OCM** (opposed coordinate motion) techniques.

## Machine Stability

Mask, part(on motion assembly), and all intervening optics(including process lens) must be maintained in a geometrically stable relationship, requiring attention to mechanical layout/construction, and often employing machine bases/frames in either natural or synthetic granite. Mechanical stability of laser source and illumination optics are less critical, though **pointing stability** of the laser must be good enough to ensure reproducibility of illumination over time.

## Vision & Environment Systems

Vision systems include TTL or other inspection optics, where magnification is selected either for **area viewing** or **fine inspection./alignment**. Adequate and flexible **part lighting** must be provided, particularly when **PRS**(pattern recognition s/w) is used for automation. We can include in vision systems **highlighting**, whereby a visible light source is positioned on the laser side of the mask(behind a dichroic mirror), so that with a suitable process lens the pattern to be machined is indicated on the part in highlight prior to actual machining.

Excimer laser processing, particularly of polymers, often benefits from a **shield gas** during processing, whilst process debris/fumes must be safely extracted from the process area.

## Process Control

Successful execution of a process usually requires coordinated and/or synchronous control of laser energy & firing, mask selection/control, & part motion. Simple repetitive tasks can be adequately controlled by PLC, but most systems use PC control, also running ancillary systems such as PRS, environment control, safety monitoring, data logging etc. In an industrial system a compromise must be sought between flexibility and reliability/freedom from operator mishandling. The ideal approach is s/w with multi-level access for operators with different skill levels,- most simply engineer/supervisor/operator.

## System Architecture

System design can only start with a knowledge of the optimum process parameters,- wavelength, energy density, shot dose etc. A central aim of many systems is then to maximize **BUF**(beam utilization factor) i.e. the % of the laser output that can be usefully transferred to the part. BUF is affected marginally by the energy losses occurring inevitably in UV optics, but principally by the pattern to be ablated, and the **machining strategy** adopted.

Consider as an example drilling of a large number of irregularly spaced small holes. Holes could easily be drilled sequentially using a simple fixed motif;- the energy used for a single one hole may be very much less than that available at the laser o/p, the limitation of throughput will be rep. rate and motion between successive holes. The most appropriate source may be a small laser, placing the accent on high rep. rate.

At the other extreme, if hole spacings are fixed but irregular, a single mask could be used to define all holes with parallel processing , limited mainly by the beam size/energy. Techniques such as OCM(Opposed Coordinate Motion) may be invoked. The geometric transparency of the mask is an important concept; clearly a uniformly illuminated mask with just isolated holes makes for an inherently low BUF. In such cases a dramatic improvement in BUF can result from matching the illumination to the mask, for e.g. using diffractive optics to direct illumination only where required on the mask, or regenerative masks where the beam is multiply reflected between the mask and a preceding mirror, effectively using the same beam several times over.. Intermediate cases may identify groups of holes which can be drilled in parallel, with step & repeat, perhaps of a number of selectable masks, possibly processing two or more parts with repositioning in masked time. All options are open!

Thus, **system architecture** results from a holistic study of the motif(s) to be machined, processing parameters, part presentation etc.,- and matching these to the characteristics of available sources & handling /motion equipment, using BDU design/optical techniques to enhance BUF and optimize throughput with guaranteed process quality; this is the role of the system architect.

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