Laser Micromachining

ME 677: Laser Material Processing
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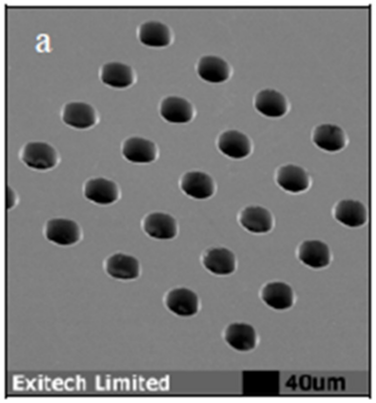
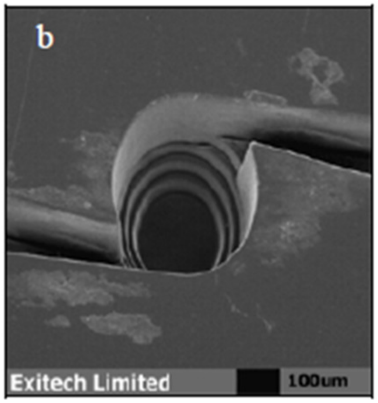
Outline

- Laser Micromachining – Introduction
- Machining by long pulses
- Machining by excimer laser
- Ultrashort pulsed machining

Laser Micromachining

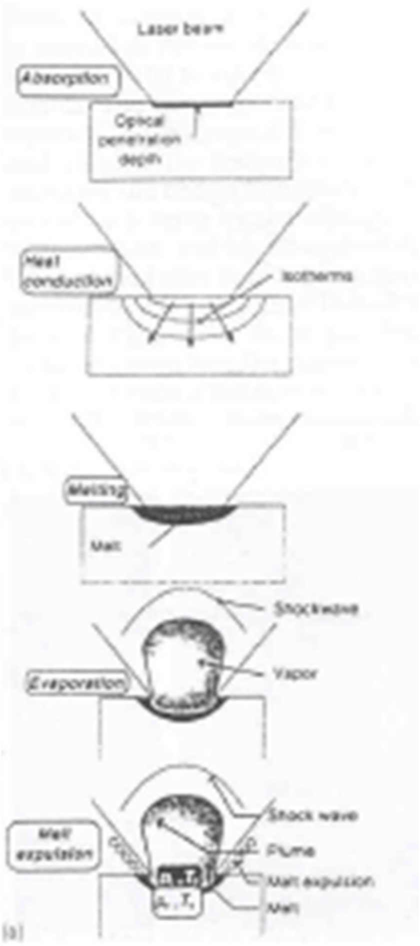
- Lasers are being used in microengineering where pulsed lasers are used
  - Ink jet nozzles
  - Lab on chip





Machining by long pulses

- Absorption
  - depends upon the w/p material
  - power density
  - Wavelength
- CO2 lasers: 5-20% absorption/Nd: YAG and excimer 40-80% is absorbed.
- The optical penetration depth power density is reduced to 1/e of the initial density
  - CO2 lasers -15 nm and Nd: YAG -5 nm.



One –Dimensional Model –Effect of pulse

$$ierfc(u) = \frac{e^{-u^2}}{\sqrt{\pi}} - u\left(1 - erf\,(u)\right)$$

$$T_{z,t} = \frac{2F_0}{k}\left\{ \alpha t^{\frac{1}{2}}\, \mathrm{ierfc}\left(\frac{z}{2\sqrt{\alpha t}}\right)\right\}$$

$$T(0,t) = (2F_0 / K)\left[(\alpha t)/\pi\right]^{0.5}$$

$$Time\_to\_vaporization$$

$$t_v = \frac{\pi}{\alpha}\left[\frac{T_B K}{2F_0}\right]^2$$

- *For $F_0 = 10^9 W/cm^2$*
- *Find tv*
- *If power density is increased 10 times find tv*

Mechanism of Machining-Long pulses

- High vaporization rate causes a shock wave
- Resulting high vapor pressure at the liquid surface increases the boiling temperature
- Material is removed by the expulsion of melt and explosive like boiling of the superheated liquid at the end of a laser pulse
- Machining of metals generate a rim of resolidified material

Images of Machining

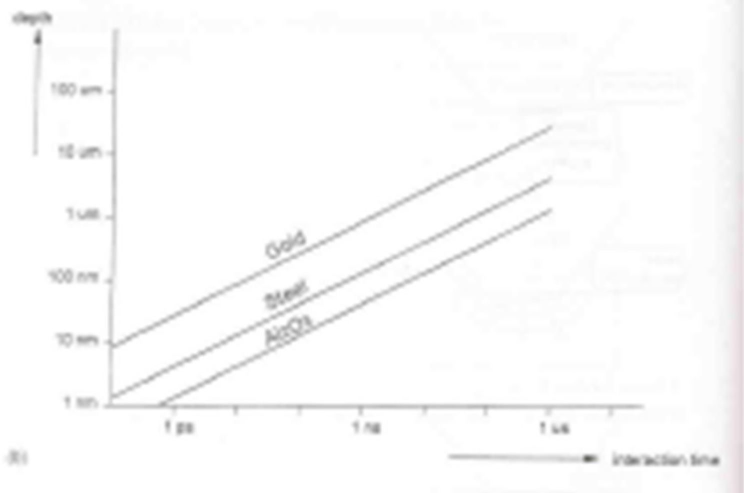


Figure 3 Continued.

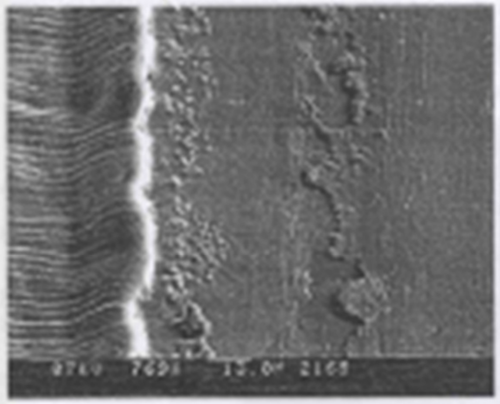
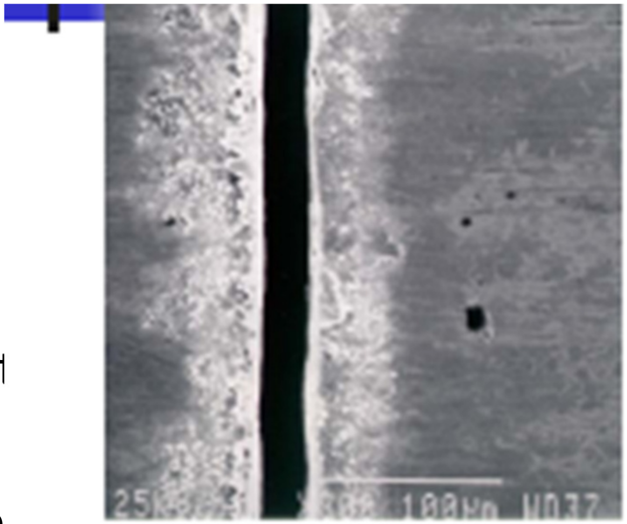


Figure 4 Rim of resolidified material after micromachining of stainless steel. Also some redeposition is evident (right): excimer laser, KrF 248 nm, 20 ns, 12 J/cm², 90 Hz. The ablation depth is 15 µm; rim height is 10 µm.

Long pulse micromchining

- Machining Example of a 25 micron (1 mil) channel machined in 1 mm (40 mils) thick INVAR with a nanosecond laser.
- INVAR, 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 b 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.



Excimer Laser Machining

- Created by IBM, Excimer lasers (the name is derived from the terms excited and dimers)
- Uses reactive Halides with inert gases
- When electrically stimulated a diatomic pseudo molecule (dimer) usually of an inert gas atom and a halide atom is produced.
- Under normal circumstances no bonding is possible. But in the excited stage chemical reaction takes place and a bond is formed
- These diatomic molecules have very short lifetimes and dissociate releasing the excitation energy through UV photons.

Excimer - Reactions

Pumping (Mirowave or gas discharge is used)

e + Kr →Kr+ + e + e

-positive inert gas ion formation

e + Kr → Kr* + e

-inert gas in metastable condition

e + F2 → F-+ F+

-negative halogen ion formation

Kr* + F-+ M → KrF* + M

-KrF production

Kr* + F2 → KrF* + F

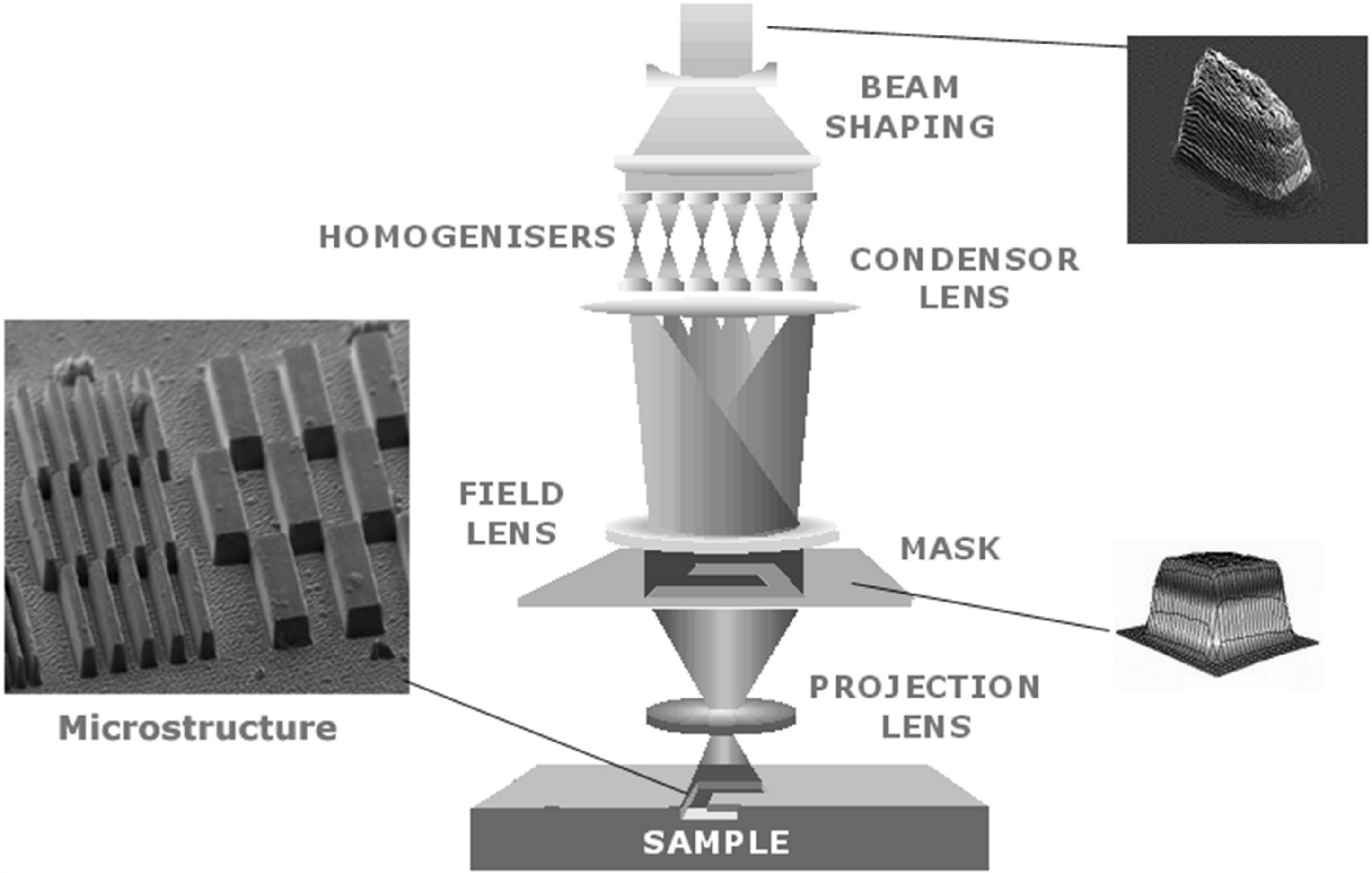
Stimulated emission

KrF* + hv → Kr + F + 2hv (248 nm) -laser emission.

Excimer Laser Properties

- Pulsed ultra-violet (UV) radiation
- Relatively broadband sources and usually have a rectangular beam output of the order of ~25mm x ~10mm
- The beam divergence is usually ∼1-5mrad and it is different in the two orthogonal beam directions
- Due to this relatively large and non-uniform beam divergence and poor spatial coherence, the direct focusing of excimer lasers is unattractive
- Hence, the technique of mask projection is commonly used

Schematic of Masking



Masking

- Output from excimer laser is not uniform and so usually some form of beam homogenisation is used for "flat-top" beam.
- This homogenisation is normally important since the ablated depth of the sample depends on the energy density of the beam at any point
- A mask used to define a shape or pattern for the formation of the desired microstructures, is placed at the plane of optimum uniformity of the beam
- It is then imaged onto the sample by appropriate high-resolution optics.
- The mask is typically either made from chrome-on-quartz or from a thin metal sheet.

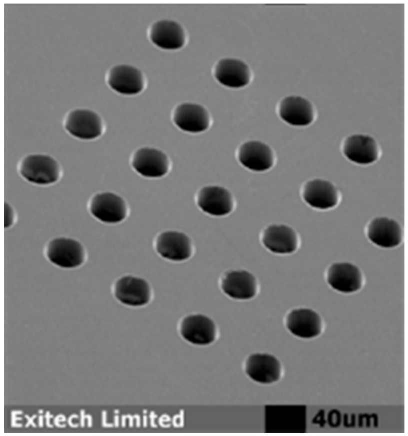
Masking

- Mask dimensions
  - The projection lens usually de-magnifies the mask pattern onto the workpiece, de-magnifications of x4, x10 or x30 are used so the mask does not have to be made of ultra-high resolution features, thereby reducing its complexity and cost of manufacture
- Mask Damage
  - Due to the de-magnification which is used, the energy density of the laser beam is much lower at the mask than at the sample. This reduces the risk of damage to the mask and increases the mask lifetime as well
- Separation of Mask and Workpiece
  - Because the mask and workpiece are not in close proximity, the mask does not suffer from any debris or particulate damage from the sample ablation
- Independent Control
  - Mask projection allows independent control of the motion of the mask and workpiece and this allows many different processing techniques to be used depending on the desired micro-engineering application

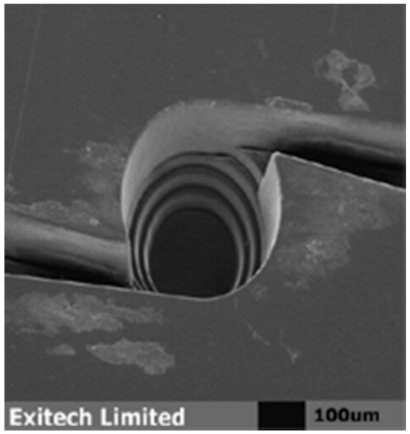
Static Mask

- *Step-and-repeat processing*
  - lateral motion of the sample in between the production of structures
  - the laser is fired with a static mask and workpiece to produce a structure; the laser is turned off; the sample is moved laterally in X or Y; the laser is fired again to produce the same structure again.
- *Indexed mask* projection
  - involves the positioning of a new mask pattern in between production of the structures
  - the laser is fired with a static mask and workpiece to produce a structure; the laser is turned off; the mask is moved laterally to position another mask pattern under the laser beam; the laser is fired again over the same workpiece area to superimpose the new mask pattern over the previous one.

Features



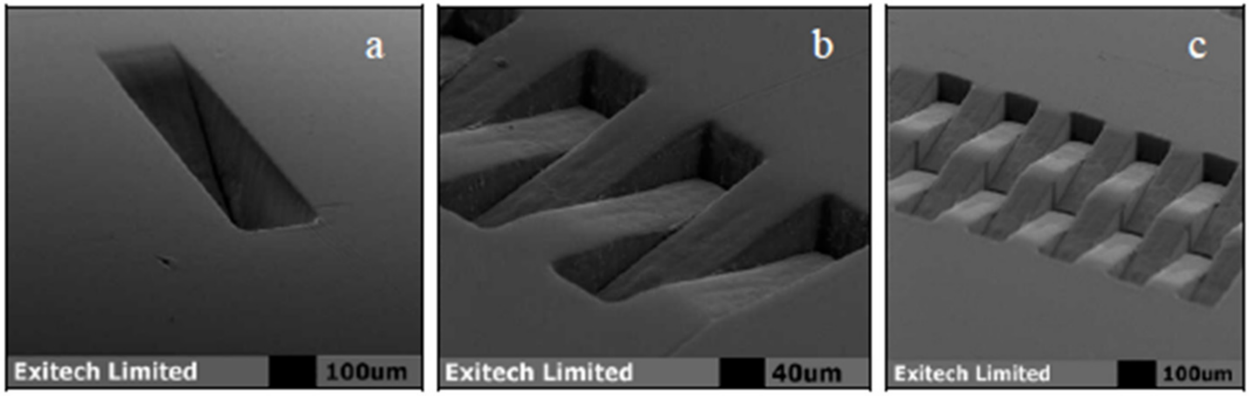
Step and Repeat



Indexed Mask

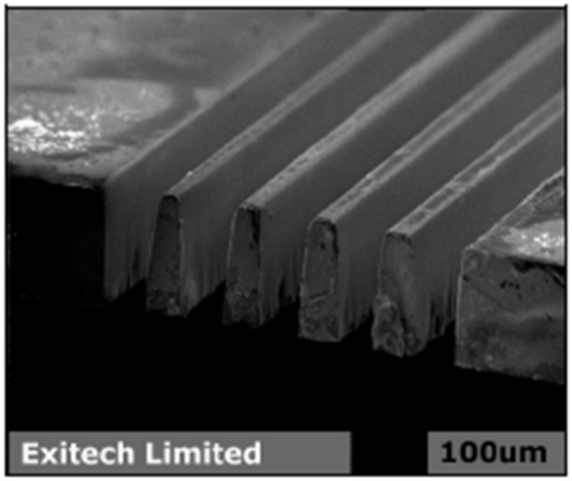
Mask Dragging

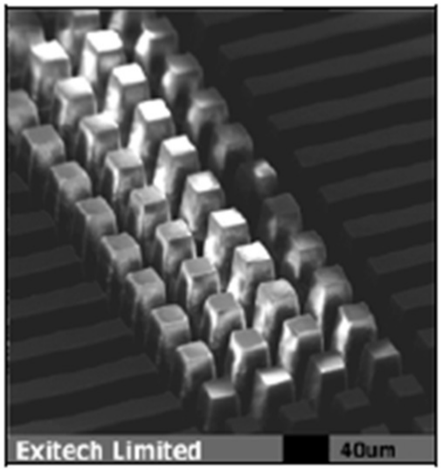
- If the mask is moved during the firing of the laser, then structures can be produced which have varying depth profiles
- This can be achieved by ensuring that an aperture moves across the laser beam in a precisely controlled manner during the laser firing
- The static workpiece is exposed to a continually-varying amount of energy across it’s exposed area which produces a depth gradient in the sample.



Workpiece Dragging

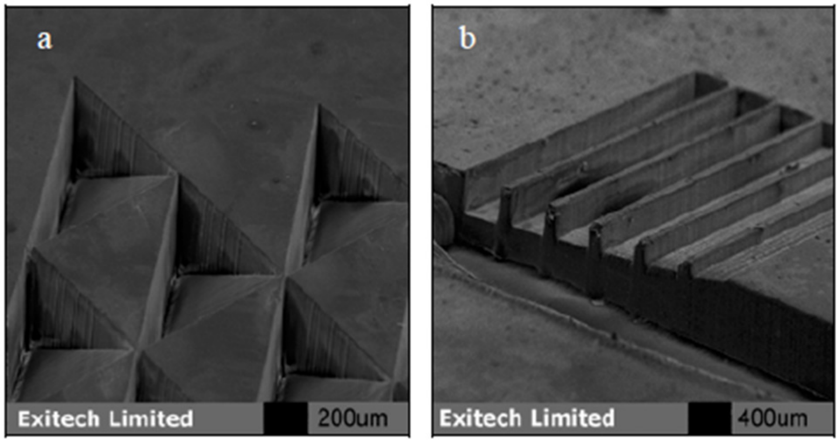
- This is one of the most common extensions of the mask projection technique and involves the movement of only the sample during the laser firing.
- It is usually associated with the production of micro-channels or micro-grooves which may be used in optics and biomedical applications





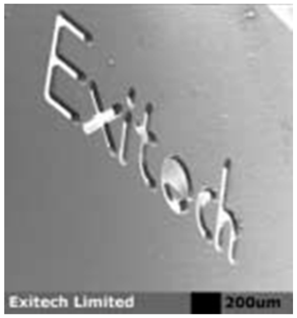
Synchronized Scanning

- *Both the mask and workpiece are moved in synchronized fashion*
- Synchronized scanning is used where the pattern to be produced is large, nonrepeating and cannot be produced by any of the three previous techniques
- It has applications in printing (where the plates used to transfer the ink to the print medium can be laser-engraved),p rinted-circuit-board industries (for the definition of the electrode patterns) and display panels (for the electrodes)



Direct Writing

- The two main advantages of direct writing are that:
  - does not require a mask.
  - the path to be machined can be fed directly into the control of the machining
  - directly interfaced to the CAD generation of the pattern



Introduction to ultra-fast pulsed lasers

- a laser capable of generating light pulses that last only a few femtoseconds
- 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

Ultra-short pulsed lasers

- Femtosecondablation: There is no transfer of energy to the lattice during this process. All the energy is stored in a thin surface layer.
- This energy will be more than the specific heat of evaporation and there will be vigorous evaporation after the incidence of the pulse. The ablation depth per pulse is given by –
- $Za \sim \alpha^{-1} \ln(Fa/Fth)$
- Where, Fa is the absorbed fluence and Fth is the threshold fluence= energy required to evaporate the irradiated volume of material; α- penetration depth (absorption). For α^{-1}= 10nm, Fth= 0.1 J/cm2.
- For the material removal to occur, fluence should be about 3 times that of the threshold fluence.
- The ablation process is a direct solid-vapor transition. The energy is transferred to the lattice from electrons after the pulse in a picosecond.
- The result is a precise and pure laser ablation of materials.

Features

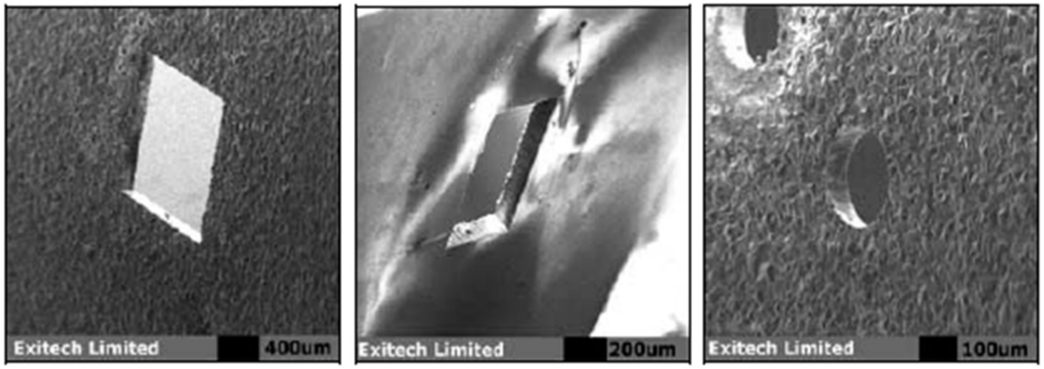


Figure 12. CVD diamond cut using a 750ps fibre laser.