TA 202A

Lecture 8

Non-Conventional Machining Processes

Laser Beam Machining (LBM)

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History and Overview of LBM

- The word laser stands for Light Amplification by Stimulated Emission of Radiation.
- Machining with laser beams, first introduced in the early 1970s, is now used routinely in many industries. Laser machining, with long or continuous wave (CW*), short, and ultra-short pulses, includes many applications:
  - Heat treatment
  - Welding
  - Ablation or cutting of plastics, glasses, ceramics, semiconductors and metals
  - Material deposition.
  - Etching with chemical assist i.e., Laser Assisted Chemical Etching (LACE)
  - Drilling
  - Additive manufacturing
  - Surgery
  - Photo-polymerization (e.g., stereo-lithography)

Laser Beam Cutting

Laser drilling process

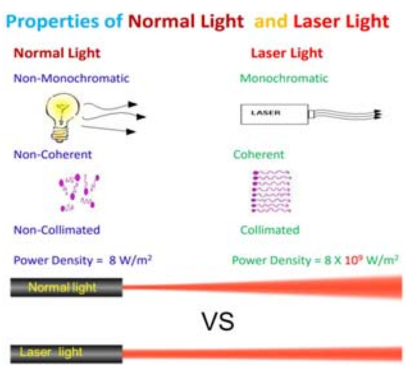
LASER

- A laser converts electrical energy into a highly coherent light beam with the following properties:
  – Monochromatic (theoretically, single wave length)
  – Highly collimated (light rays are almost perfectly parallel)
- These properties allow laser light to be focused, using optical lenses, onto a very small spot with resulting high power densities

Laser is essentially an optical amplifier that

✓ **Generates and**

✓ **Amplifies** → **Stimulated Emission**



Laser Components:

- **Lasing Medium:**
  Provides appropriate transition and determines the wavelength (it must be in a metastable state)
- **Pumping Energy Source:**
  Provides energy necessary for population inversion
- **Optical Cavity:**
  Provides opportunity for amplification and Produces a directional beam (with defined length and transparency)

Classification of Lasers

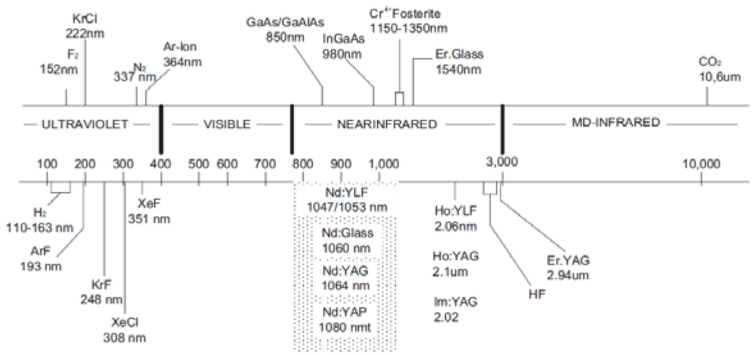
- Laser can be classified by its lasing medium, which is the medium that allows for the emission of coherent radiation.
- Three major categories of lasing mediums are solid, gas, and semiconductor.

Category	Lasing medium		Wavelength (λ) (nm)
Solid	Ruby		694.3
	Nd:YAG ($Y_3Al_5O_{12}$)		1064
	Nd-glass (glass rod doped with 2–6% Neodymium)		1054–1062
Gas	CO_2		10,600
	Excimer	F_2	157
		ArF	193
		KrCl	222
		KrF	248
		XeCl	308
		XeF	351
Semiconductor	GaAs (gallium arsenide)		840
	GaN (gallium nitride)		405
	InGaAs (indium gallium arsenide)		980

Nd:YAG= Neodymium: Yttrium Aluminium Garnet

Solid laser is usually used in pulse model and has low-pulsing frequency (1–2 pulse/s).

Wavelength of Laser for LBM

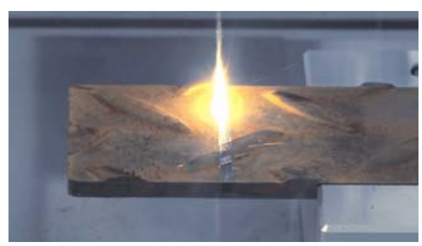


YAG: Yttrium aluminium garnet
YAP: Yttrium aluminium perovskite
YLF: Yttrium lithium fluoride
HF: Hydrogen fluoride

Types of Lasers

* Two types of lasers: continuous wave and pulsed (wave) lasers
* Long pulsed and short pulsed lasers

Continuous wave laser

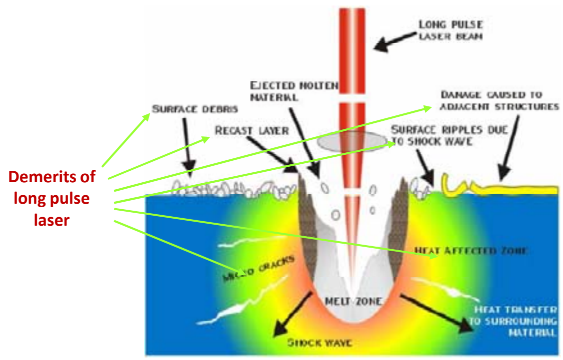


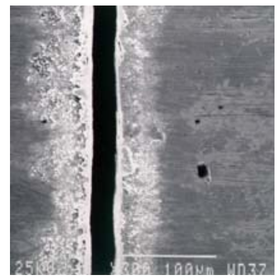
Pulsed wave laser

TIME SCALE

Millisecond	1×10^{-3} second
Micro second	1×10^{-6} second
Nano second	1×10^{-9} second
Pico second	1×10^{-12} second
Femto second	1×10^{-15} second

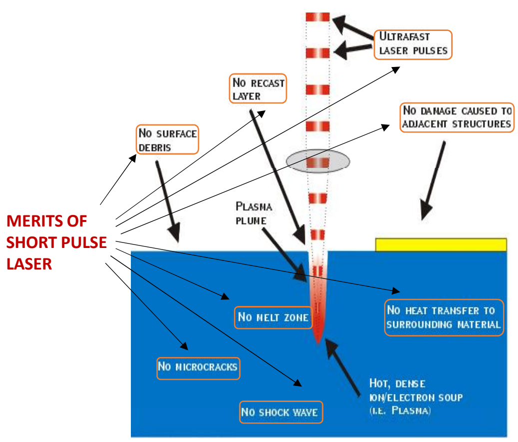
Long Pulse Laser Machining

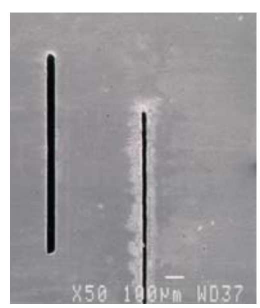




- The pulse duration in this example is 8 ns and the energy 0.5 mJ. Example of a 25 µm channel machined in 1 mm thick INVAR with a nanosecond laser. INVAR is extremely stable.
- This sample was machined using a "long" pulse laser.
- A recast layer can be clearly seen near the edges of the channel.
- Large debris are also seen in the vicinity of the cut.

Short Pulse Laser Machining





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

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Main Characteristics of Industrial Lasers

Laser type	Mode	Beam characteristics			Comments
		W_{av} (W)	f_r (p/s)	d_f (μm)	
CO_2	P	250–5000	400	75	High efficiency, bulky
	CW	100–2000	–	75	
	CW (transverse)	2500–15,000	–	75	
Nd:YAG	P	100–500	1–10,000	13	Compact, economical
	CW	10–800	–	13	
Nd:glass	P	1–2	0.2	25	Often uneconomical
Excimer	P	~100	10–500		Micromachining, plastic, ceramic

W_{av} = Average power, f_r = Pulse/s, and d_f = Focus diameter
CW: continuous wave, P: pulsed

CO_2 Lasers

- CO_2 laser is a common laser source for high-power laser machining.
- CO_2 laser uses CO_2 gas as the lasing medium and is characterized by their long wavelength of 10,600 nm, which is in the infrared (IR) range
- A mixture of gases is also used (CO_2:N_2:He = 0.8:1:7). In this case, helium acts as a coolant for the gas cavity.
- The CO_2 lasers can operate in both *CW* and *P* modes.
- The *CW* CO_2 ranges from *mW* to *GW*, which leads to broad applications:
  - Industrial applications: Engraving, Machining, Welding etc.
  - Medical procedures, such as skin resurfacing: Water, the major composition of the tissue, absorbs the CO_2 laser very well and makes it suitable for surgical cutting and joining applications.

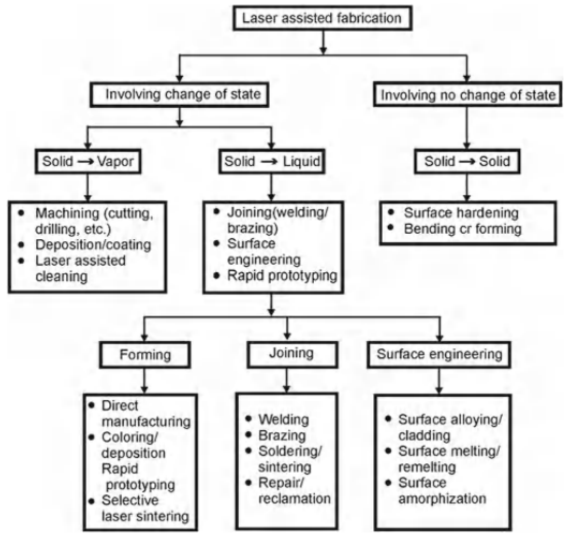
Nd:YAG Lasers

- Nd:YAG is a common lasing medium used in industry and medicine.
- YAG laser sometimes is superior to CO_2 laser because it emits a shorter wavelength.
- It is a single crystal of YAG doped with 1 % neodymium, and can operate in either CW or P mode.
- Nd:YAG laser has relatively high efficiency and pulsing frequency.
- In manufacturing industry, Nd:YAG laser is common for cutting, welding, engraving, and marking of metals and plastics with power typically ranging from 1 to 5 kW.
- In medical field, Nd:YAG laser is utilized in cutting of soft tissue (hair, skin, prostate, etc.), ophthalmology (e.g., posterior capsulotomy), and laser-induced thermotherapy.

Excimer Lasers

- Excimer is an abbreviation of “excited dimmer.”
- The beam is generated due to fast electric discharging in a mixture of high-pressure dual gas, composed of one from the halogen gas group (F, H, Cl) and another from the rare gas group (Kr, Ar, Xe).
- The wavelength of the excimer laser attains a value from 157 to 351 nm, which is in the UV region of the spectrum.
- Excimer lasers have low wavelengths and high photon energy, so they can remove or ablate material photochemically (instead of the thermal melting or vaporization), and have remarkable precision and efficiency in the microscale machining applications for plastics and biological tissues.
- It is common in semiconductor high-resolution photolithography (e.g., deep UV of KrF and ArF), ophthalmology (e.g., laser-assisted in situ keratomileusis, LASIK), and removal of plaque inside the blood vessels in peripheral artery (e.g., laser athrectomy using XeCl).

Laser Assisted Manufacturing



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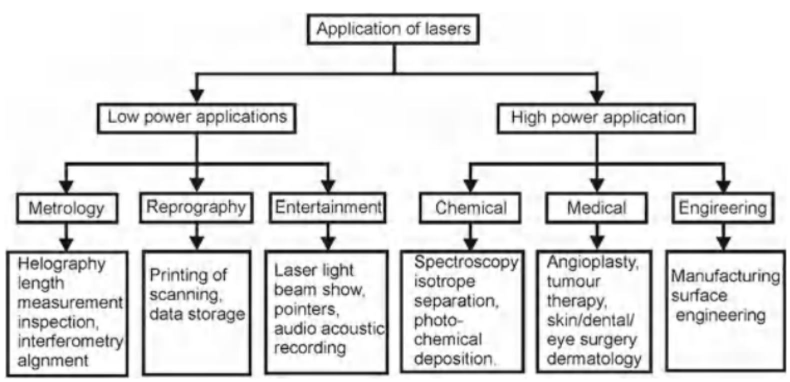
Applications of Laser



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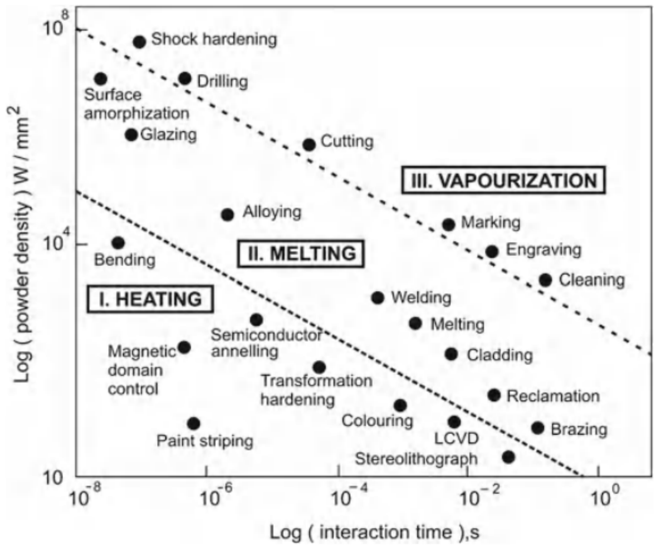
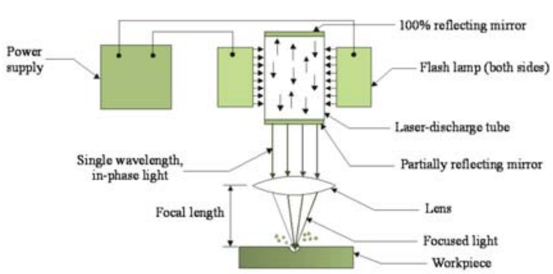
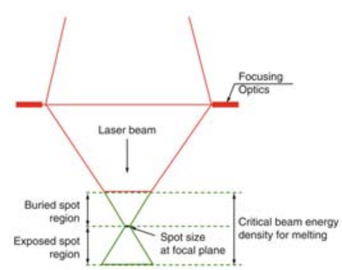


Schematic process map in terms of combination of laser power density and interaction time for different types of laser material processing involving either no (only heating) or change of state (melting or vaporization)

Laser Beam Machining

LBM: Uses the light energy from a laser to remove material by vaporization & ablation



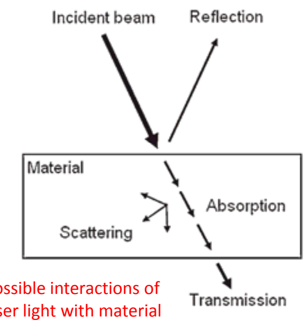


- When a laser is focused to a small spot size, there is a region above and below the focal plane where the laser energy density is high enough to form a melt pool.
- If the substrate surface is either too far above or too far below the focal plane, no melt pool will form.
- Gas is blown into the cut to clear away molten metals, or other materials in the cutting zone.
- In some cases, the gas jet can be chosen to react chemically with the workpiece to produce heat and accelerate the cutting speed (LACE)

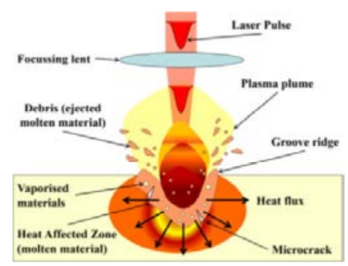
LBM Material Removal Mechanisms and Processes

Interactions of laser light with material

- Material removal mechanisms of LBM can be classified by laser's interaction with the workpiece and dependent on the wavelength of the laser beam.
- Laser beam interacts with the workpiece material either thermally or chemically.
- When the Laser beam (electromagnetic radiation) is incident on the surface of a material, various phenomena occur:
  - ➢ Reflection
  - ➢ Refraction
  - ➢ Absorption
  - ➢ Scattering
  - ➢ Transmission
- The unreflected light is absorbed, thus heating the surface of the workpiece.
- Absorption of the radiation is one of the most desirable and important phenomena in the laser processing of materials.

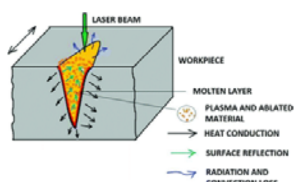


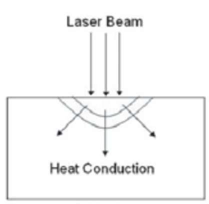
Possible interactions of laser light with material



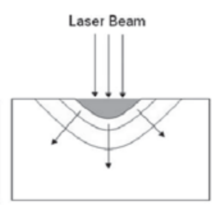
Various Effects of Laser–Material Interaction

Absorption of radiation in the materials results in various effects such as heating, melting, vaporization, plasma formation, etc., which forms the basis of several laser materials-processing techniques

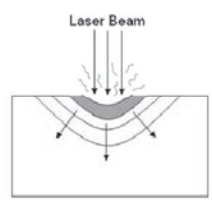




Heating

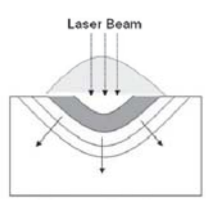


Surface melting

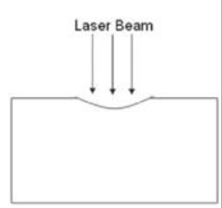


Surface vaporization

- If sufficient energy is absorbed, then the vibration becomes so intense that the molecular bonding is stretched so far that it is no longer capable of exhibiting mechanical strength and the material is said to have melted.
- On further heating, the bonding is further loosened owing to the strong molecular vibrations and the material is said to have evaporated.
- Vapour can also absorb energy but up to limited extent due to bound electrons.
- When vapour absorbs sufficient energy, their electrons get free and it turns into the plasma.
- Plasmas can be strongly absorbing if their free-electron density is high enough.



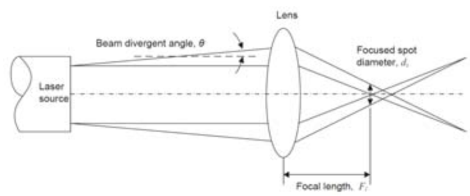
Plasma formation



Ablation

- In thermal-based LBM, the work material removal occurs by melting and vaporization of the work material.
- This mechanism is used mainly in applications such as cutting, drilling, welding, and surface hardening.
- The material removal rate (MRR) depends on the workpiece (e.g., thickness, surface roughness, and orientation) and material properties, such as thermal conductivity, specific heat, latent heat for melting and vaporization, and surface reflectivity.
- When power density reaches a threshold value (typically more than 106 W/cm^2), evaporation of material on the surface will become a high-density plasma, resulting in reduced absorption of the laser beam.
- This is called the plasma shielding effect. The ultrashort pulse, such as femtosecond, laser could potentially avoid this plasma shielding effect using the ablation (not thermal) material removal mechanism.

Power Density in LBM



A model to study the thermal-based LBM percussion drilling

The input and focus of LBM are converted to thermal energy to vaporize the workpiece material.

The size of the spot diameter $d_s$ds is determined by:

$$d_s = F_1\theta$$

F_1:focal length, θ: beam divergence angle (rad)

The area of the laser beam at focal point, A_s, is:

$$A_s = \frac{\pi}{4}(F_1\theta)^2$$

The power of the laser beam, L_p, is given by:

$$L_p = \frac{E_s}{\Delta t}$$

E_s:Laser energy (in the unit of J)
Δt: Pulse duration of the laser

The power density of the laser beam, P_d (in the unit of W/mm^2), is given by:

$$P_d = \frac{L_p}{A_s} = \frac{4L_p}{\pi(F_1\theta)^2}$$

Material Removal (MRR) in LBM

LBM occurs when the power density of the beam is greater than what is lost by thermal conduction, convection, and radiation.

The drilling feed rate *f* (in the unit of mm/s) can be described as:

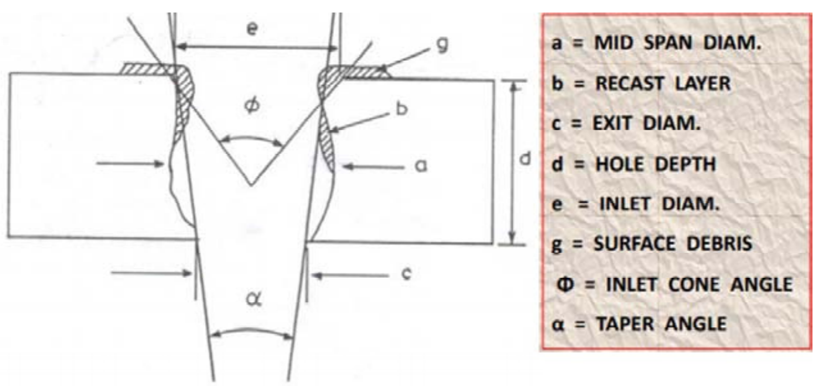
$$f = \frac{C_l L_p}{E_v A_s} = \frac{C_l P_d}{E_v}$$

where C_l: Conversion efficiency which depends on the material
E_v: Vaporization energy of the workpiece material (J/mm³)

The MRR can be calculated as follows:

$$\mathrm{MRR} = A_s f = \frac{C_l L_p}{E_v}$$

Process Characteristics



Geometry of a drilled hole using LBM process:

$$\tan\left(\frac{\alpha}{2}\right) = \left(\frac{e-c}{2d}\right)$$

Advantages of LBM

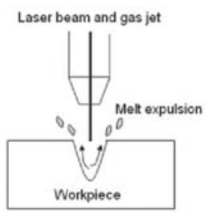
- Capable of machining a wide variety of metallic and non-metallic Materials
- Low mechanical force and deformation of the workpiece
- No diffraction and capable of simultaneously working at different workstations
- Generating micro features in difficult-to-machine and refractory materials
- Capable of controlling the beam characteristics to adapt to a specific machining needs
- No requirement for time-consuming vacuum as in electron beam machining (EBM)

Limitations of LBM

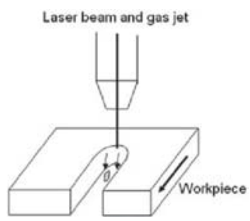
- High equipment cost
- Occupational safety concern, particularly for eyes of operators
- Limited dimensional and form accuracy and surface quality
- Difficult to machine blind holes with precise depth
- Tapered hole geometry
- Low machining efficiency (η commonly less than 1 %)
- Difficult to avoid the heat-affected zone (HAZ)
- Recast layer needed to be removed

Application of LBM

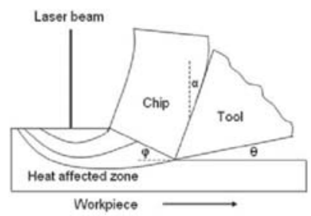
- Drilling, slitting, slotting, scribing, and marking operations
- Drilling small diameter holes - down to 0.025 mm (0.001 in)
- Generally used on thin stock
- Work materials: metals with high hardness and strength, soft metals, ceramics, glass and glass epoxy, plastics, rubber, cloth, and wood



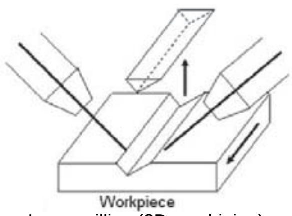
Laser drilling (1D machining)



Laser cutting (2D machining)



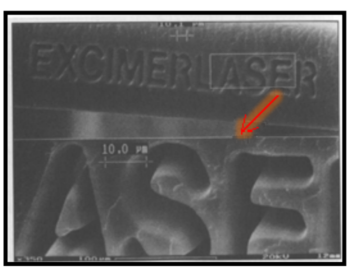
Laser-assisted machining



Laser milling (3D machining)

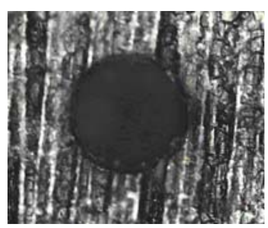
APPLICATION	LASER TYPE
Cutting	
Metals	PCO_2; $CWCO_2$; Nd:YAG; ruby
Plastics	$CWCO_2$
Ceramics	PCO_2
Drilling	
Metals	PCO_2; Nd:YAG; Nd:glass; ruby
Plastics	Excimer
Marking	
Metals	PCO_2; Nd:YAG
Plastics	Excimer
Ceramics	Excimer
Surface treatment (metals)	$CWCO_2$
Welding (metals)	PCO_2; $CWCO_2$; Nd:YAG; Nd:glass; ruby

Laser Micro Machining

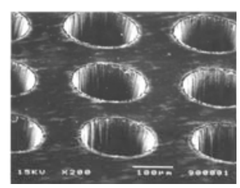


Micro machined letters on a single human hair

Note the clarity of the letters in the close-up view



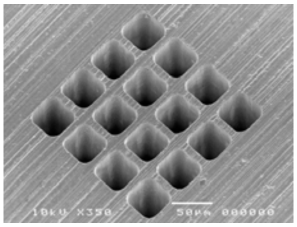
170 micron hole drilled on ceramic matrix composite

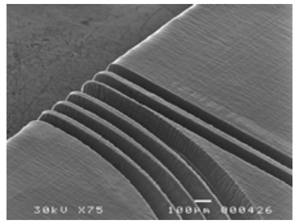


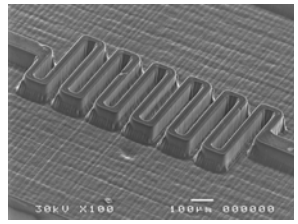
200 micron hole array on Ti-6Al-4V alloy

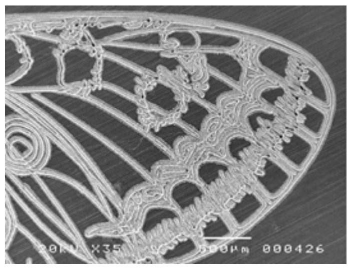
Micro pattern machined on a steel plate in less than 0.5 seconds

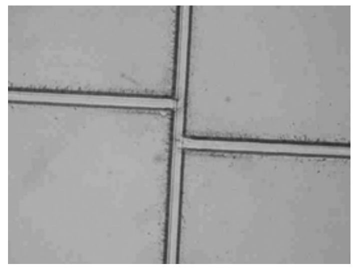
Application of Laser Micro Machining


Laser drilling


Laser cutting


Micro milling

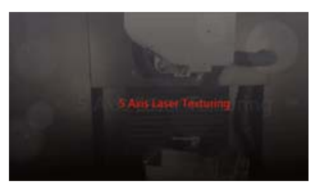

Marking and engraving


Scribing and dicing

Laser Surface Treatment

- The electromagnetic radiation of a laser beam is absorbed within the first few atomic layers for opaque materials, such as metals.
- There are no associated hot gas jets or eddy currents and there is even no radiation spillage outside the optically defined beam area.
- Common advantage of laser surfacing over other process:

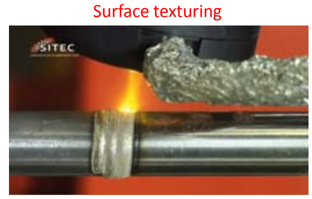
  1. Chemical cleanliness.
  2. Controlled thermal penetration and therefore less distortion.
  3. Less after-machining, if required.
  4. Controlled thermal profile and HAZ.


Surface texturing

Examples of laser surface treatment

- Surface heating
- Surface melting
- Surface alloying
- Surface cladding
- Surface texturing
- Surface roughening
- Micromachining
- Laser marking


Surface roughening


Surface cladding

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Laser heat treatment

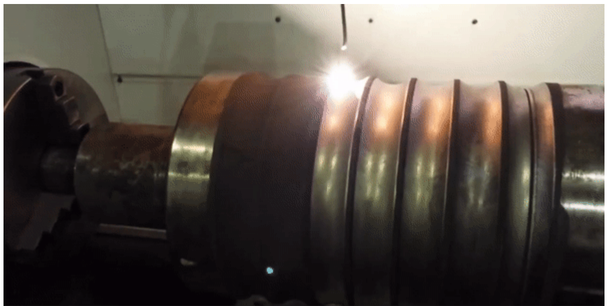
- As the beam moves over an area of the metal surface, the temperature starts to rise and thermal energy is conducted into the metal component.
- Temperatures must rise to values that are more than the critical transformation temperature but less than the melt temperature.
- After the beam has passed, cooling occurs by quenching from the bulk of the material which has hardly been heated by this fast surface heating process.
- The laser beam is defocused or oscillated to cover an area such that the average power density is 10^3–10^4 W mm^{-2}.
- Using these power densities, a relative motion between the workpiece and the beam will result in **surface hardening**.

Laser Surface Melting

- Laser surface melting uses similar method as laser surface hardening but in this case a focused or nearly focused beam is used.
- The surface to be melted is shrouded by an inert gas.
- The main characteristics are:
  1. Moderate to rapid solidification rate produces fine near-homogenous structure.
  2. Little thermal penetration thus less distortion.
  3. Surface finish can be achieved nearly 25µm.

Laser Surface Alloying

- Laser surface alloying is similar to laser surface melting except that another material is injected into the melt pool.
- Laser surface alloying is also similar to laser cladding in that if the cladding process is performed with excess power.
- Laser surface alloying is capable of producing a wide variety of surface alloys.
- The laser offers precision in the placement of the alloy, good adhesion and vastly improved processing speeds.



Laser alloying for repairing the steel rolls by RHJR 850

Recap of This Lecture

- History and overview of LBM
- Types of lasers
- LBM - Material removal mechanisms and processes
- Material removal rate (MRR) in LBM
- Applications of LBM

Next Lecture

Additive Manufacturing/ 3D Printing