Thermal Energy Based Removing Techniques

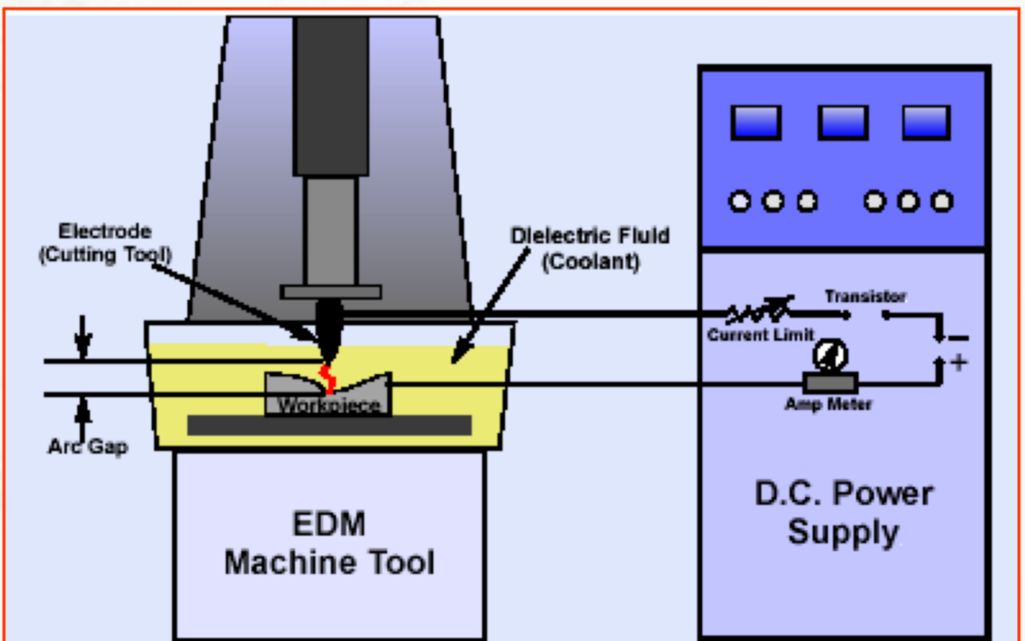
- Sinker electrical discharge machining (EDM) and wire EDM
- Laser beam machining
- Electron beam machining
- Plasma arc cutting
- What is a laser?

Thermal Removing Techniques

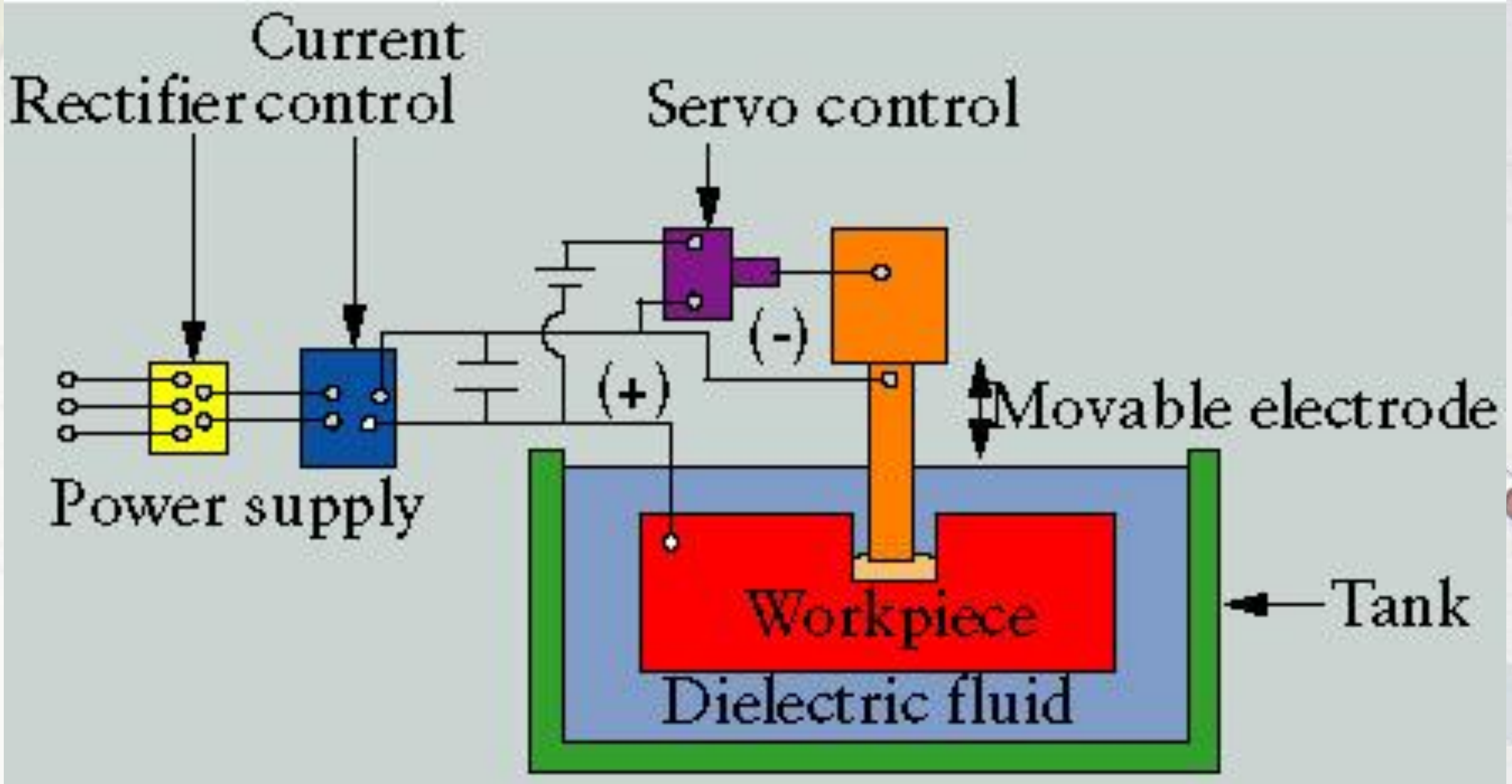
- In thermal removing processes, thermal energy, provided by a heat source, melts and/or vaporizes the volume of the material to be removed.
- Among thermal removal methods, electrical discharge machining or EDM is the oldest and most widely used. Electron-beam (EBM) and laser beam machining (LBM) are newer thermal techniques also widely accepted in industry today. Plasma-arc cutting using a plasma arc torch is mostly used for cutting relatively thick materials in the range of 3 to 75 mm and is less pertinent to most miniaturization science applications.
- In thermal removal processes, a heat-affected zone (HAZ), sometimes called a recast layer, is always left on the work-piece. In electron-beam, laser, and arc machining deposition as well as removal methods are available.

Electrical Discharge Machining- EDM

- In die-sinking EDM systems, the electrode (cutting tool) and work-piece are held by the machine tool. A power supply controls the electrical discharges and movement of the electrode in relation to the work-piece.
- During operation the work-piece is submerged in a bath of dielectric fluid (non-conducting). (Die-Sinking EDM is also called Sinker, Conventional, Plunge or Vertical EDM). SEE utube



Electrical Discharge Machining-EDM

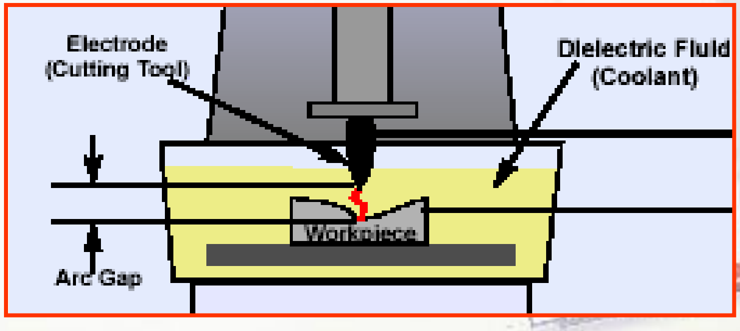


Schematic illustration of the electrical-discharge-machining process.

Based on erosion of metals by spark discharge. The cavity is is formed by the shape of the electrode.

Electrical Discharge Machining- EDM

- During normal operation the electrode never touches the work-piece, but is separated by a small spark gap.
- The electrode (plunger) can be a complex shape, and can be moved in X, Y, and Z axes, as well as rotated, enabling more complex shapes with accuracy better than one mil. (this is called CNC plunger EDM)
- The spark discharges are pulsed on and off at a high frequency cycle and can repeat 250,000 times per second. Each discharge melts or vaporizes a small area of the work piece surface.
- Plunge EDM is best used in tool and die manufacturing, or for creating extremely accurate molds for injection-molding plastic parts.
- The amount of material removed from the work piece with each pulse is directly proportional to the energy it contains.

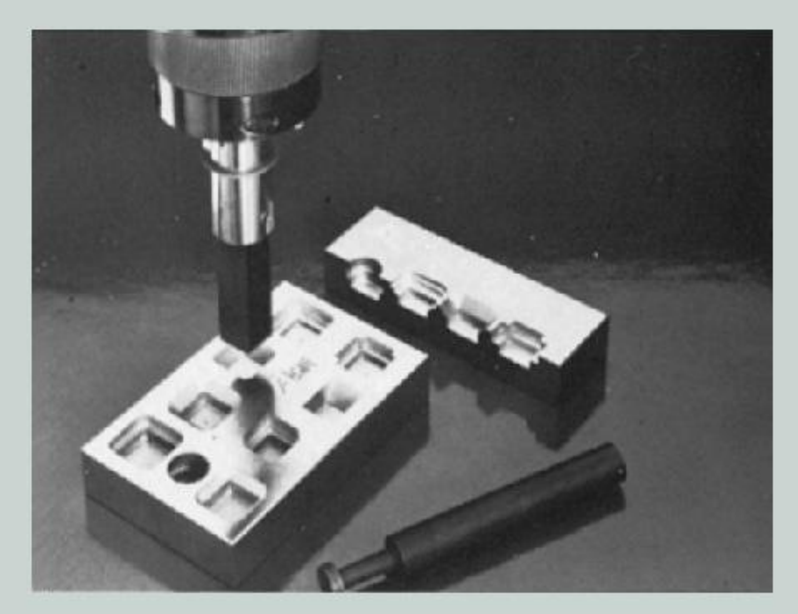


Electrical Discharge Machining- EDM

- The dielectric fluid in EDM performs the following functions:
  - It acts as an insulator until sufficiently high potential is reached .
  - Acts as a coolant medium and reduces the extremely high temp. in the arc gap.
  - More importantly, the dielectric fluid is pumped through the arc gap to flush away the eroded particles between the work-piece and the electrode which is critical to high metal removal rates and good machining conditions.
- A relatively soft graphite or metallic electrode can easily machine hardened tool steels or tungsten carbide. One of the many attractive benefits of using the EDM process.

Electrical Discharge Machining-EDM

- Stepped cavities produced with a square electrode by EDM. The workpiece moves in the two principal horizontal directions, and its motion is synchronized with the downward movement of the the electrode to produce various cavities
- Also shown is a round electrode capable of producing round or eliptical cavities. Obviously, this is done under computer control (CNC plunger



Electrical Discharge Machining-EDM

- Surface finish is affected by gap voltage, discharge current, and frequency
- The EDM process can be used on any material that is an electrical conductor
- The EDM process does not involve mechanical energy, therefore, materials with high hardness and strength can easily be machined.
- Applications include producing die cavity for large components, deep small holes, complicated internal cavities
- EDM is not a fast method; some jobs can take days to produce holes, so its use is limited to jobs that cannot easily be done in other ways (e.g. oblong slots or complex shapes, sometimes in very hard material).
- Note too the work must be conductive so it does not work on materials such as glass or ceramic, or most plastics.

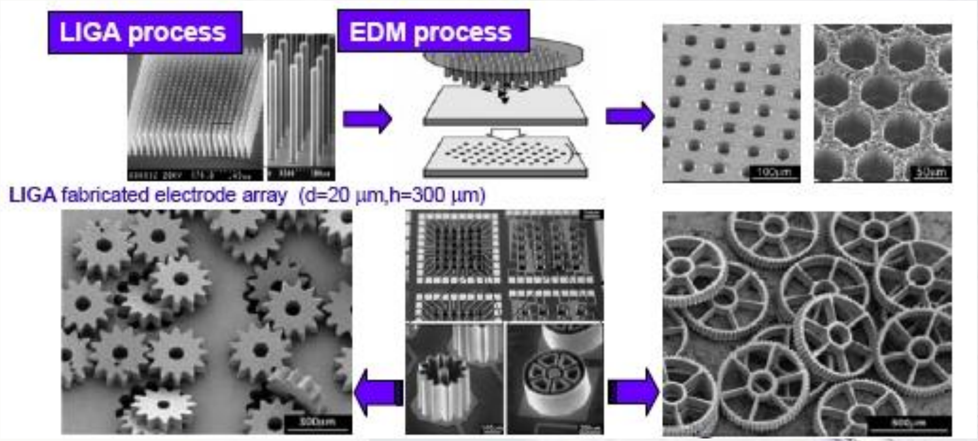
Typical use	Hard, machining of brittle metals, tool making
Tool	Carbon, zinc, brass, copper, silver-tungsten or copper-tungsten
Dielectric medium	Distilled water (DI), petroleum oils, silicones, triethylene, glycol water mixtures
Aspect ratio of holes	As high as 100:1
Surface finish	1 to 3 μm but even 0.25 μm has been reported
Gap size/voltage	25 μm/80 V
Removal rate	0.001 to 0.1 cm^3/hr
Workpiece	Conductor

Electrical Discharge Machining-EDM

- When referring to micro electrical discharge machining (μ-EDM) one refers either to working with a small EDM machine (see Figure for a hand-held EDM at Panasonic) or to working with smaller than usual electrodes (in sinker EDM) or with thinner wires (in EDM-WC).

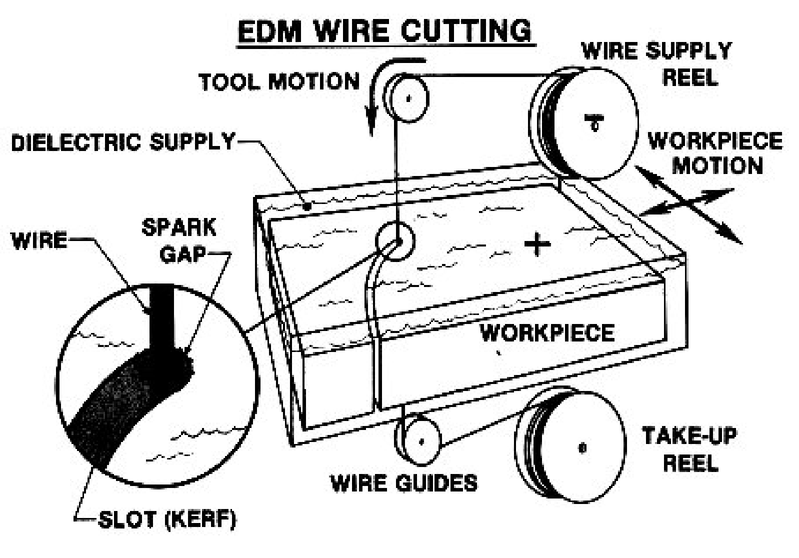
Batch Electrical Discharge Machining- EDM

- The use of microelectrode arrays enables one to use µ-EDM in batch mode as pioneered by Takahata
- Takahata employed the LIGA process to make microelectrode arrays.
- Structures made with this hybrid LIGA-EDM method are shown in the Figure on the right.



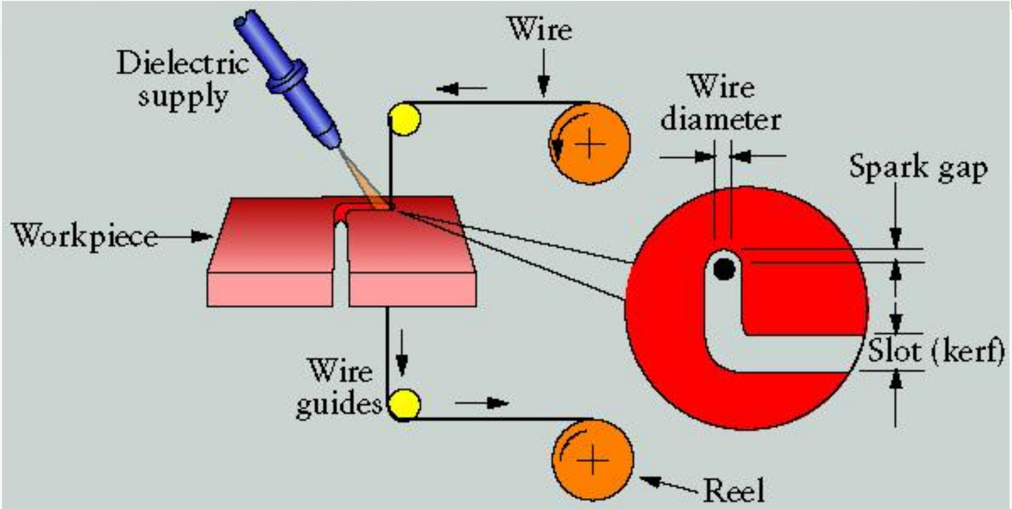
Wire Electrical Discharge Machining

- Electrical discharge machining wire cutting (EDM-WC) is a thermal mass-reducing process that uses a continuously moving wire to remove material by means of rapid controlled repetitive spark discharges.
- A dielectric fluid is used to flush the removed particles, regulate the discharge, and keep the wire and workpiece cool. The wire and workpiece must be electrically conductive.



Wire Electrical Discharge Machining

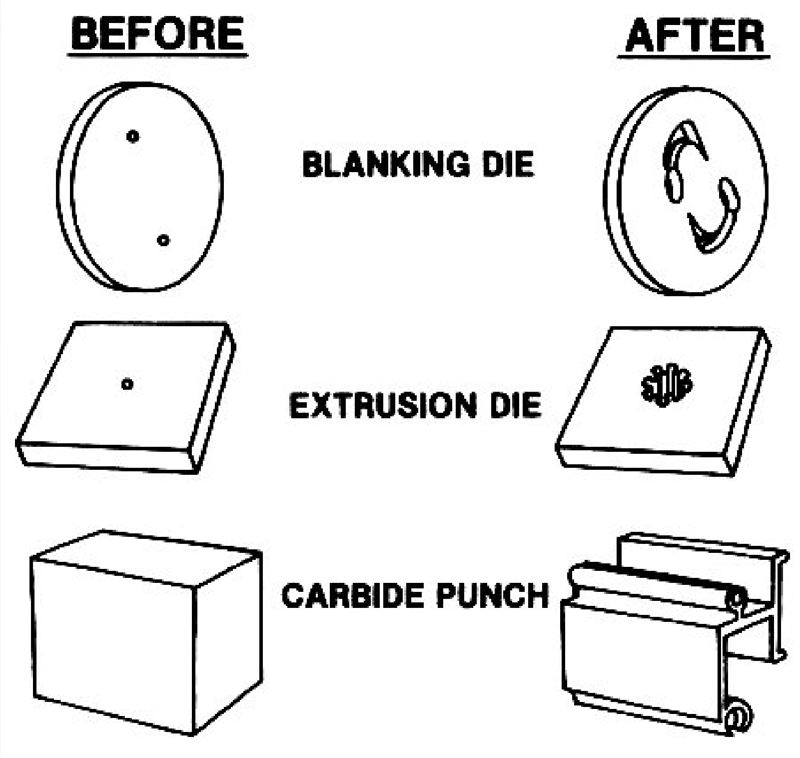
- Schematic illustration of the wire EDM process. As much as 50 hours of machining can be performed with one reel of wire, which is then discarded.



Typical EDM-WC products.

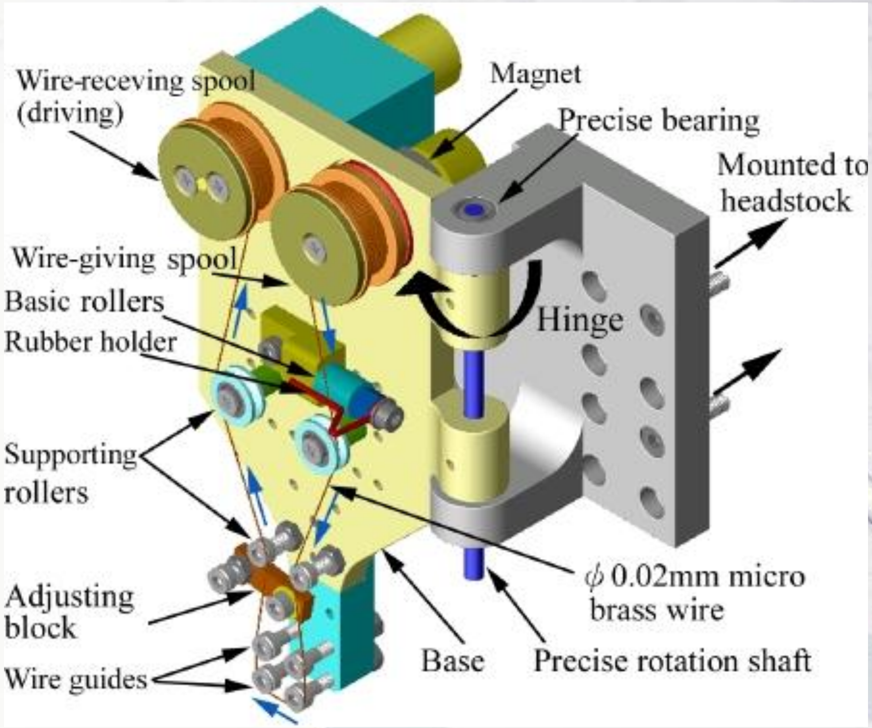
Wire Electrical Discharge Machining

- Utilizes a traveling wire that is advance within arcing distance of the workpiece (0.001 in.)
- Removes material by rapid, controlled, repetitive spark
- Uses dielectric fluid to flush removed particles, control discharge, and cool wire and workpiece
- Is performed on electrically conductive workpieces
- Can produce complex two-dimensional shapes



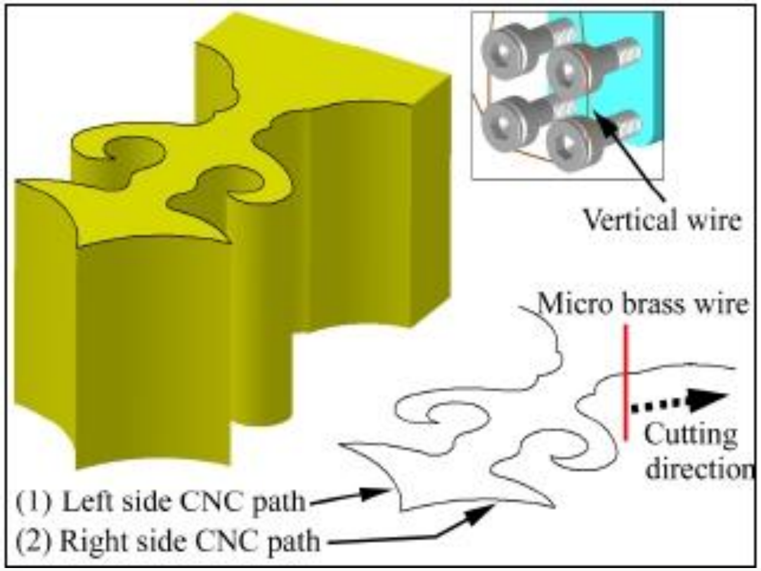
Wire Electrical Discharge Machining

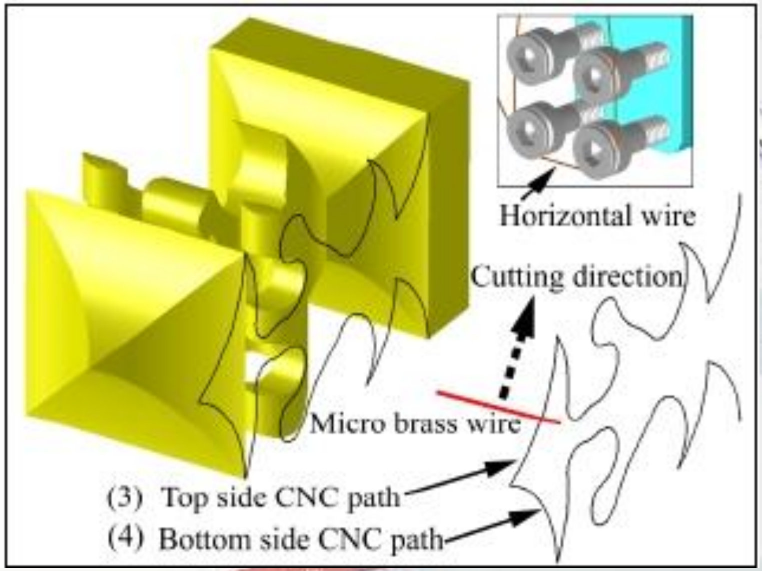
- Numerically controlled wire EDM has revolutionized die making, particularly for plastic molders. Wire EDM is now common in tool-and-die shops. Shape accuracy in EDM-WC in a working environment with temperature variations of about 3° C is about 4 μm. If temperature control is within ± 1° C, the obtainable accuracy is closer to 1 μm.
- No burrs are generated and since no cutting forces are present, wire EDM is ideal for delicate parts.
- No tooling is required, so delivery times are short. Pieces over 16 in thick can be machined. Tools and parts are machined after heat treatment, so dimensional accuracy is held and not affected by heat treat distortion.



Wire Electrical Discharge Machining

- The vertical, horizontal and slanted cutting with the μ-EDM-WC tool has successfully fabricated complex features and parts.
- An example is the impressive Chinese pagoda (1.25 mm × 1.75 mm) shown here where vertical and horizontal μ-EDM-WC cuts are illustrated

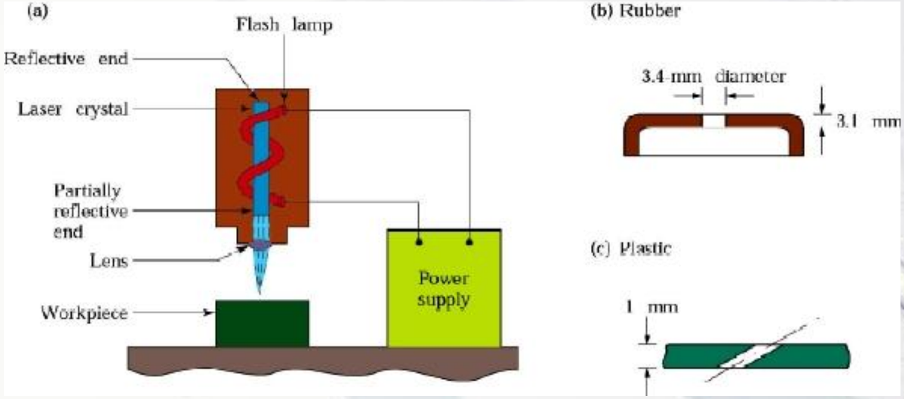




Laser Beam Machining

- 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 the following 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 or LACE
  - Laser-enhanced jet plating and etching
  - Lithography
  - Surgery
  - Photo-polymerization (e.g., μ-stereo-lithography)

*In laser physics and engineering the term "continuous wave" or "CW" refers to a laser which produces a continuous output beam, sometimes referred to as 'free-running'.



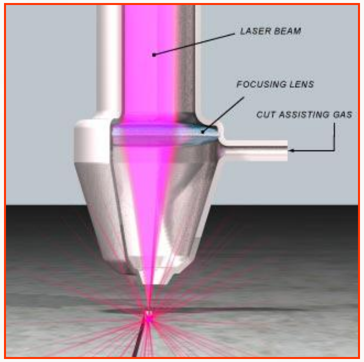
(a) Schematic illustration of the laser-beam machining process. (b) and (c) Examples of holes produced in non-metallic parts by LBM.

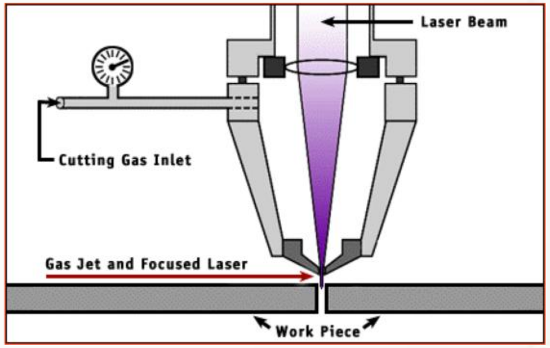
Nd: YAG : neodymium-doped yttrium aluminum garnet is a crystal that is used as a lasing medium for solid-state lasers. ...

Laser Beam 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

Note: P = pulsed, CW = continuous wave.





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)

Laser Beam Machining

- A laser machine consists of the laser, some mirrors or a fiber for beam guidance, focusing optics and a positioning system. The laser beam is focused onto the work-piece and can be moved relatively to it. The laser machining process is controlled by switching the laser on and off, changing the laser pulse energy and other laser parameters, and by positioning either the work-piece or the laser focus.
- Laser machining is localized, non-contact machining and is almost reaction-force free. Photon energy is absorbed by target material in the form of thermal energy or photochemical energy. Material is removed by melting and blown away (long pulsed and continuous-wave lasers), or by direct vaporization/ablation (ultra-short pulsed lasers). Any material that can properly absorb the laser irradiation can be laser machined. The spectrum of laser machinable materials includes hard and brittle materials as well as soft materials. The very high intensities of ultra-short pulsed lasers enable absorption even in transparent materials.

Laser Beam Machining

- Pulsed lasers (beam waist):

w ~ Òbeam waistÓ or 1/e^2 radius

~ *be careful, 1/e radius is used for calculating electric field*

~ *µm to mm*

~ *20 to 40 µm for Nd:YAG harmonic lasers w optics*

$$I(r) = I_0 \cdot e^{-\frac{2r^2}{w^2}}$$

I_0 ~ axial intensity

w ~ beam waist (i.e. 1/e^2 radius)

At r = w, the I(r) is at 1/e^2 (13.5%) of the axial intensity, I_0.

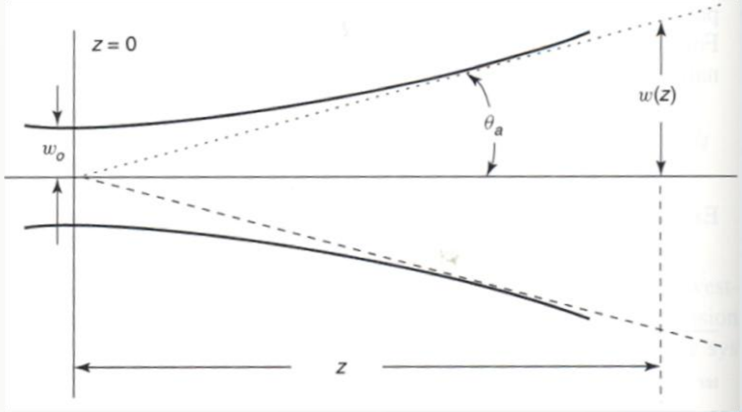
Laser Beam Machining

- For a given beam, I_0 will be at a maximum in the focal plane where $w = w_0$, the minimum beam waist.

$$P_{total} = \int I(r)\, dA = \int_0^{\infty} I_0 \cdot e^{-\frac{2r^2}{w^2}}\, 2\pi r\, dr$$

$$P_{total} = \frac{w^2 \cdot I_0 \cdot \pi}{2}$$

$$\therefore \quad I_0 = \frac{2 \cdot P_{total}}{\pi \cdot w^2}$$



Laser Beam Machining

w_0 = min. waist; = w_f waist in the focal plane

z_R ~ Rayleigh range (or confocal parameter)

$$z_R = \frac{\pi \cdot n \cdot w_0^{\ 2}}{\lambda_0}$$

n ~ index of refraction (approx. 1 for air)

λ_0 ~ free space wavelength

$$w^2 = w_0^{\ 2}\left[1 + \left(\frac{z}{z_R}\right)^2\right]$$

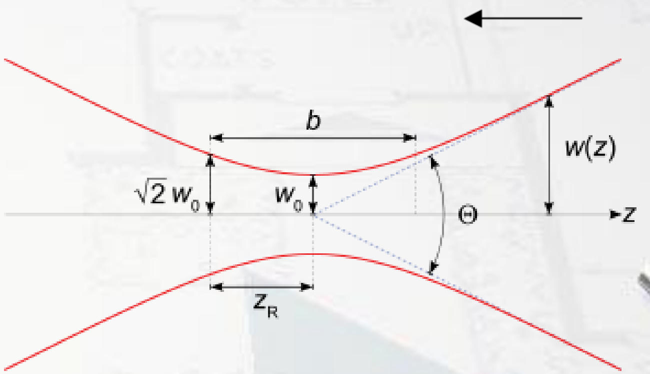
- The parameter w(z) approaches a straight line for z >>> z_R
- The angle between this straight line and the central axis of the beam is called the divergence of the beam. It is given by

$$\theta \simeq \frac{\lambda}{\pi w_0} \qquad (\theta \text{ in radians.})$$

Laser Beam Machining

At z = 0, the minimum beam waist, w_0 (w_f), is:

$$w_o = w_f = \frac{\lambda_0 \cdot f}{\pi \cdot n \cdot w_{in}}$$



where

- ***w_f Ğ1/e^2 beam waist in the focal plane***
- ***f Ğfocal length of lens***
- ***w_{in} Ğbeam waist into the lens (at z =-f)***
- ***n Ğindex of refraction (approx. 1 for air)***

Laser Beam Machining:DOF=2.Z$_R$

$$w^2 = w_0{}^2\left[1+\left(\frac{z}{z_R}\right)^2\right]$$

At z = ± z_R:

$$w = \sqrt{2}\cdot w_f = \sqrt{2}\cdot w_0$$

so I_0 is decreased by 2X.

$$I_0 = \frac{2\cdot P_{total}}{\left(\sqrt{2}\cdot w_f\right)^2\cdot\pi}$$

The distance between these two points is called the *confocal parameter or depth of focus of the beam:*

$$\therefore\ d \approx 2\cdot z_R$$

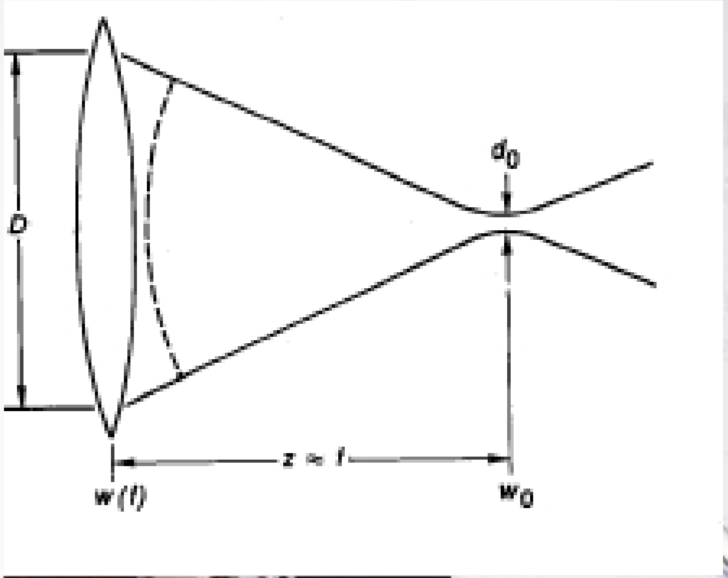
Laser Beam Machining

- If a "perfect" lens (no spherical aberration) is used to focus a collimated laser beam, the minimum spot size radius or the focused waist (w_0) is limited by diffraction only and is given by (f is the focal length of the lens) :

$$w_0 = \frac{\lambda f}{\pi w_{lens}}$$

- With $d_0 = 1/e^2$ the diameter of the focus (= $2w_0$) and with the diameter of the lens $D_{lens}=2w_{lens}$ (or the diameter of the laser beam at the lens –whatever is the smallest) we obtain:

$$d_0 = \frac{4\lambda f}{\pi D_{lens}} = \frac{1.27\lambda f}{D_{lens}}$$

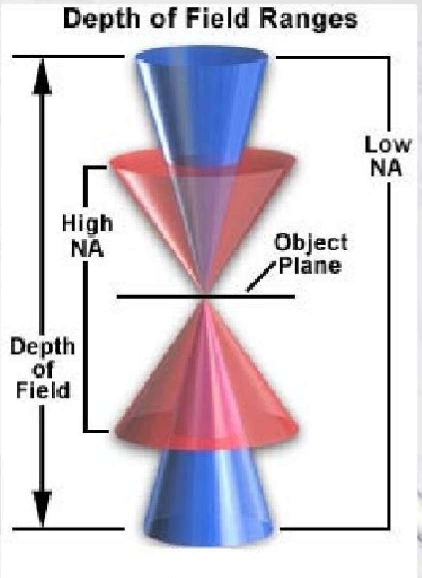


Laser Beam Machining

- Thus, the principal way of increasing the resolution in laser machining, as in photolithography, is by reducing the wavelength, and the smallest focal spot will be achieved with a large-diameter beam entering a lens with a short focal length.
- Twice the Raleigh range or 2 z_R is called the "depth of focus" because this is the total distance over which the beam remains relatively parallel, or "in focus" (see Figure).
- Or also, the depth of focus or depth of field (DOF) is the distance between the values where the beam is √2 times larger than it is at the beam waist. This can be derived as (see also earlier) :

$$DOF = 1.27\lambda/NA^2$$

- Material processing with a very short depth of focus requires a very flat surface. If the surface has a corrugated topology, a servo-loop connected with an interferometric auto ranging device must be used.



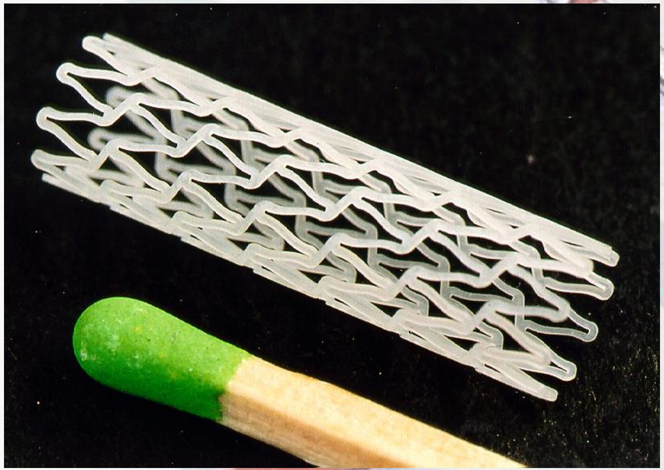
Laser Beam Machining

- Laser ablation is the process of removal of matter from a solid by means of an energy-induced transient disequilibrium in the lattice. The characteristics of the released atoms, molecules, clusters and fragments (the dry aerosol) depend on the efficiency of the energy coupling to the sample structure, i.e., the material-specific absorbance of a certain wavelength, the velocity of energy delivery (laser pulse width) and the laser characteristics (beam energy profile, energy density or fluency and the wavelength).

Laser Parameter	Influence on Material Processing
Power (average)	Temperature (steady state) Process throughput
Wavelength (μm)	Optical absorption, reflection, transmission, resolution, and photochemical effects
Spectral line width (nm)	Temporal coherence Chromatic aberration
Beam size (mm)	Focal spot size Depth of focus Intensity
Lasing modes	Intensity distribution Spatial uniformity Speckle Spatial coherence Modulation transfer function
Peak power (W)	Peak temperature Damage/induced stress Nonlinear effects
Pulse width (sec)	Interaction time Transient processes
Stability (%)	Process latitude
Efficiency (%)	Cost
Reliability	Cost

Laser Beam Machining

- More specifically for micromachining purposes, the wavelength, spot size [i.e., the minimum diameter of the focused laser beam, d_0 , average laser beam intensity, depth of focus, laser pulse length and shot-to-shot repeatability (stability and reliability in the Table) are the six most important parameters to control.
- Additional parameters, not listed in the Table , concerns laser machining in a jet of water and laser assisted chemical etching (LACE)-see below.



PHB stent

Laser Beam Machining:Heat Affected Zone - HAZ

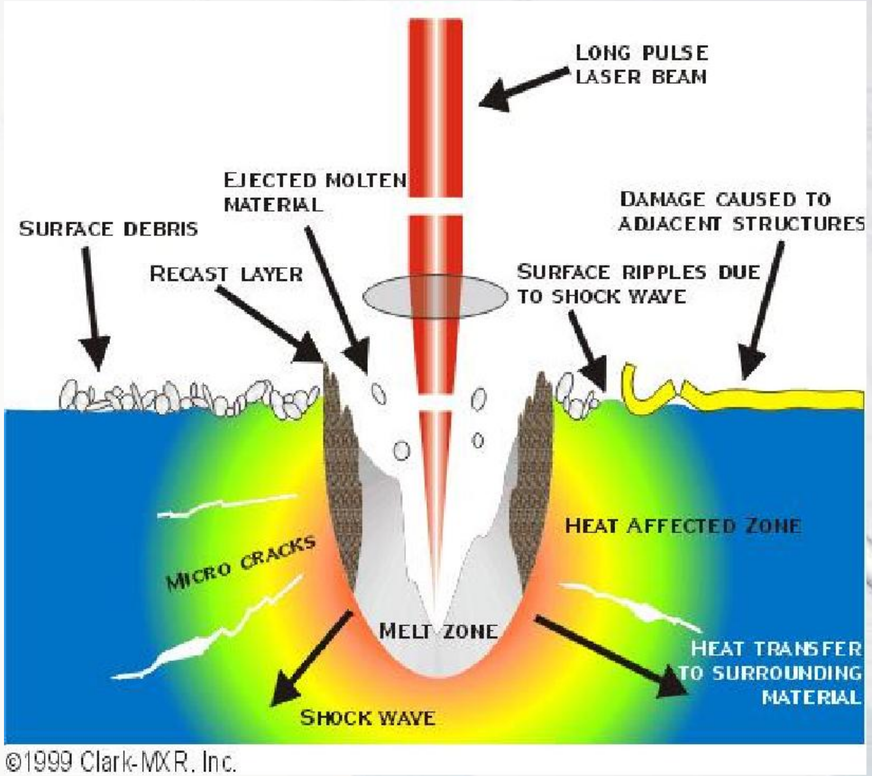
- The most fundamental feature of laser/material interaction in the long pulse regime (e.g., pulse duration 8 ns, energy 0.5 mJ) is that the heat deposited by the laser in the material diffuses away during the pulse duration; that is, the laser pulse duration is longer than the heat diffusion time. This may be desirable for laser welding, but for most micromachining jobs, heat diffusion into the surrounding material is undesirable and detrimental to the quality of the machining (http://www.clark-mxr.com).
- Here are reasons why one should avoid heat diffusion for precise micromachining:
  - Heat diffusion reduces the efficiency of the micromachining process as it takes energy away from the work spot—energy that would otherwise go into removing work piece material. The higher the heat conductivity of the material the more the machining efficiency is reduced.

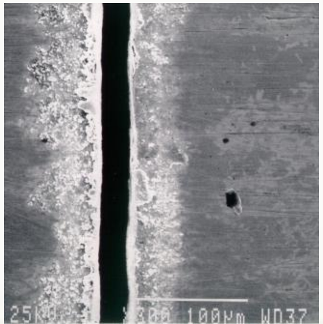
Laser Beam Machining:Heat Affected Zone - HAZ

- Heat-diffusion affects a large zone around the machining spot, a zone referred to as the heat-affected zone or HAZ. The heating (and subsequent cooling) waves propagating through the HAZ cause mechanical stress and may create micro cracks (or in some cases, macro cracks) in the surrounding material. These defects are "frozen" in the structure when the material cools, and in subsequent routine use these cracks may propagate deep into the bulk of the material and cause premature device failure. A closely associated phenomenon is the formation of a recast layer of material around the machined feature. This resolidified material often has a physical and/or chemical structure that is very different from the unmelted material. This recast layer may be mechanically weaker and must often be removed.
- Heat-diffusion is sometimes associated with the formation of surface shock waves. These shock waves can damage nearby device structures or delaminate multilayer materials. While the amplitude of the shock waves varies with the material being processed, it is generally true that the more energy deposited in the micromachining process the stronger the associated shock waves.

Long Pulse Laser Beam Machining

- The various undesirable effects associated with long laser pulse etching are illustrated here.
- The pulse duration in this example is 8 ns and the energy 0.5 mJ Example of a 25 µm (1 mil) channel machined in 1 mm (40 mils) 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.





(http://www.clark-mxr.com).

Short Pulse Laser Beam Machining

- Ultra-short laser pulses have opened up many new possibilities in laser-matter interaction and materials processing. The extremely short pulse width makes it easy to achieve very high peak laser intensity with low pulse energies. The laser intensity can reach $10^{14} \sim 10^{15} W/cm^2$ with a pulse < 1mJ when a sub-pico-second pulse is focused to a spot size of a few tens of micrometers.

Short Pulse Laser Beam Machining

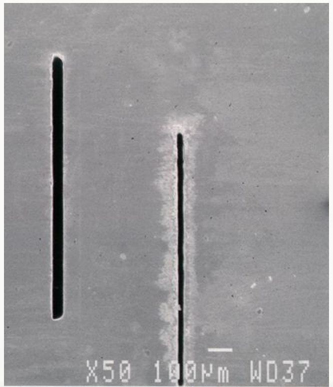
- Using short pulses laser intensity easily reaches the hundreds of terawatts per square centimeter at the work spot itself. No material can withstand the ablation forces at work at these power densities. This means that, with ultrafast laser pulses, very hard materials, such as diamond, as well as materials with extremely high melting points, such as molybdenum and rhenium, can be machined. The most fundamental feature of laser-matter interaction in the very fast pulse regime is that the heat deposited by the laser into the material does not have time to move away from the work spot during the time of the laser pulse. The duration of the laser pulse is shorter than the heat diffusion time. This regime has numerous advantages as listed below (http://www.clark-mxr.com/industrial/handbook/introduction.htm):

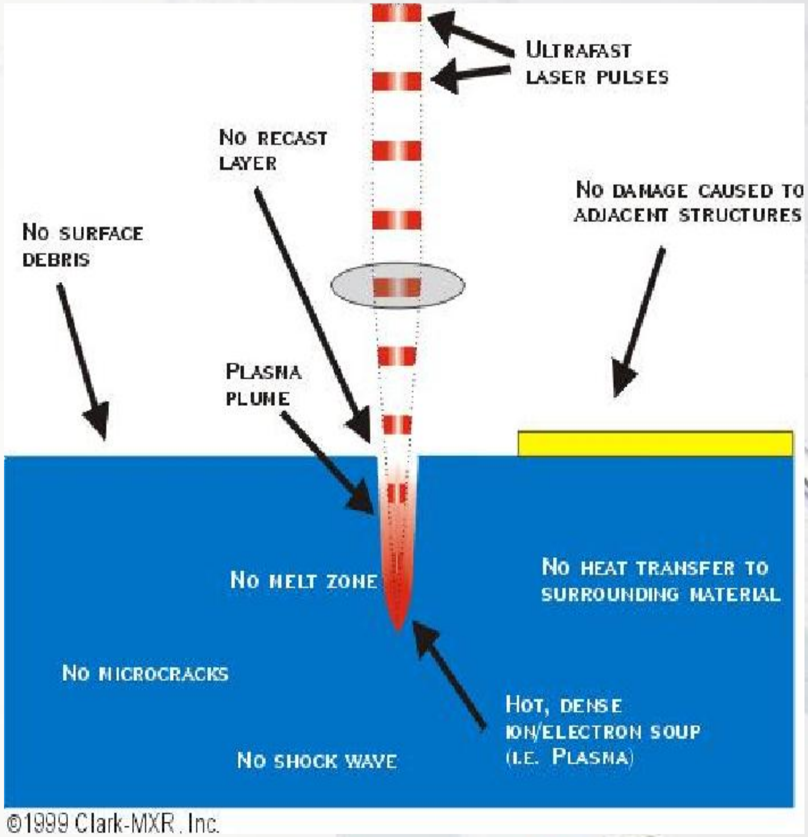
Short Pulse Laser Beam Machining

- Because the energy does not have the time to diffuse away, the efficiency of the machining process is high. Laser energy piles up at the level of the working spot, whose temperature rises instantly past the melting point of the material and keeps on climbing into what is called the plasma regime.
- After the ultra-fast laser pulse creates the plasma at the surface of the work-piece, the pressures created by the forces within it cause the material to expand outward from the surface in a highly energetic plume or gas. The internal forces that previously held the material together are vastly insufficient to contain this expansion of highly ionized atoms and electrons from the surface. Consequently, there are no droplets that condense onto the surrounding material. Additionally, since there is no melt phase, there is no splattering of material onto the surrounding surface.

Short Pulse Laser Beam 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.



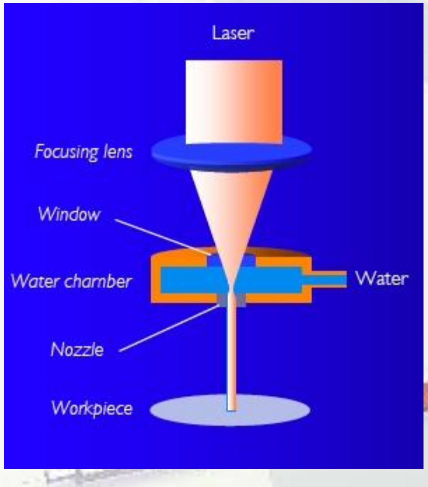


Laser Beam Machining

- Advantages:
  - Excellent control of the laser beam with a stable motion system achieves an extreme edge quality. Laser-cut parts have a condition of nearly zero edge deformation, or roll-off
  - It is also faster than conventional tool-making techniques.
  - Laser cutting has higher accuracy rates over other methods using heat generation, as well as water jet cutting.
  - There is quicker turnaround for parts regardless of the complexity, because changes of the design of parts can be easily accommodated. Laser cutting also reduces wastage.
- Disadvantages:
  - The material being cut gets very hot, so in narrow areas, thermal expansion may be a problem.
  - Distortion can be caused by oxygen, which is sometimes used as an assist gas, because it puts stress into the cut edge of some materials; this is typically a problem in dense patterns of holes.
  - Lasers also require high energy, making them costly to run.
  - Lasers are not very effective on metals such as aluminum and copper alloys due to their ability to reflect light as well as absorb and conduct heat. Neither are lasers appropriate to use on crystal, glass and other transparent materials.

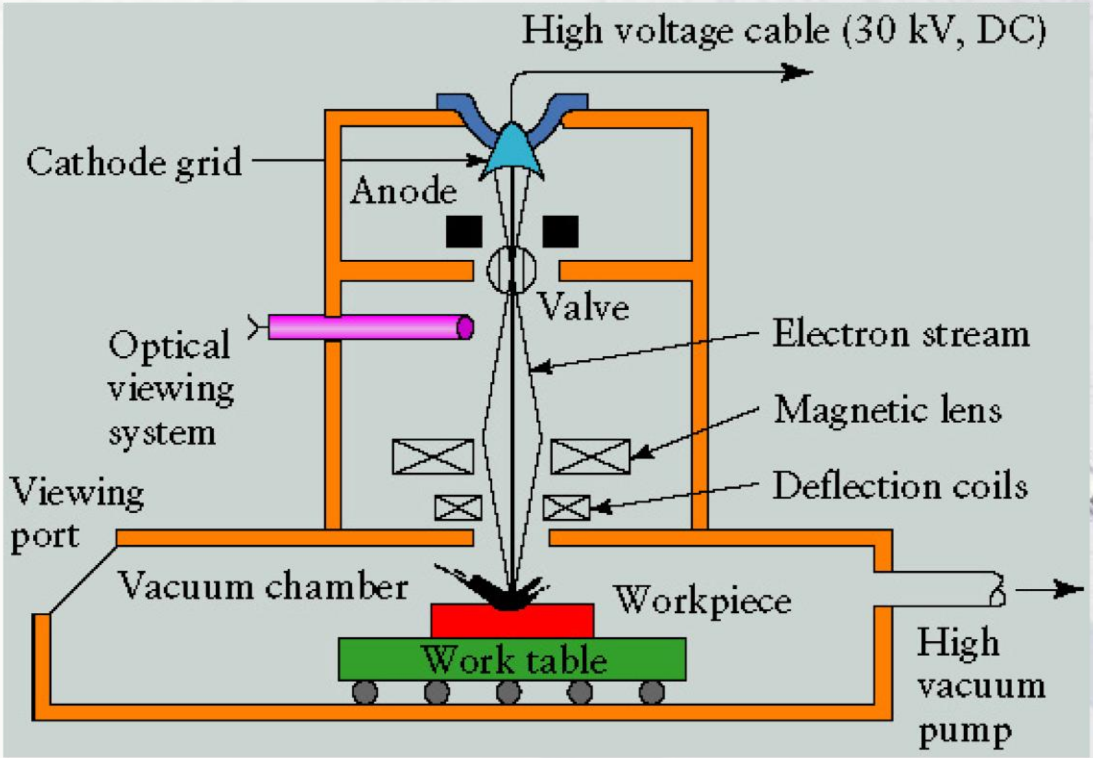
Water Jet Guided Laser Machining

- In water jet guided laser machining, a thin jet of high-pressure water (the diameter of the jet is between 40 and 100µm and the water pressure is between 20 and 500 bars) is forced through a nozzle (made of diamond or sapphire). The laser beam is focused through a water chamber (the water is de-ionized and filtered) into a nozzle as shown in the Figure.
- Briefly discuss LACE i.e., laser assisted chemical etching



Electron Beam Machining

- Electron-beam removal of materials is another fast-growing thermal technique. Instead of electrical sparks, this method uses a stream of focused, high-velocity electrons from an electron gun to melt and vaporize the work-piece material.
- In EBM, electrons are accelerated to a velocity of 200,000 km/s or nearly three-fourths that of light.



Plasma Beam Machining

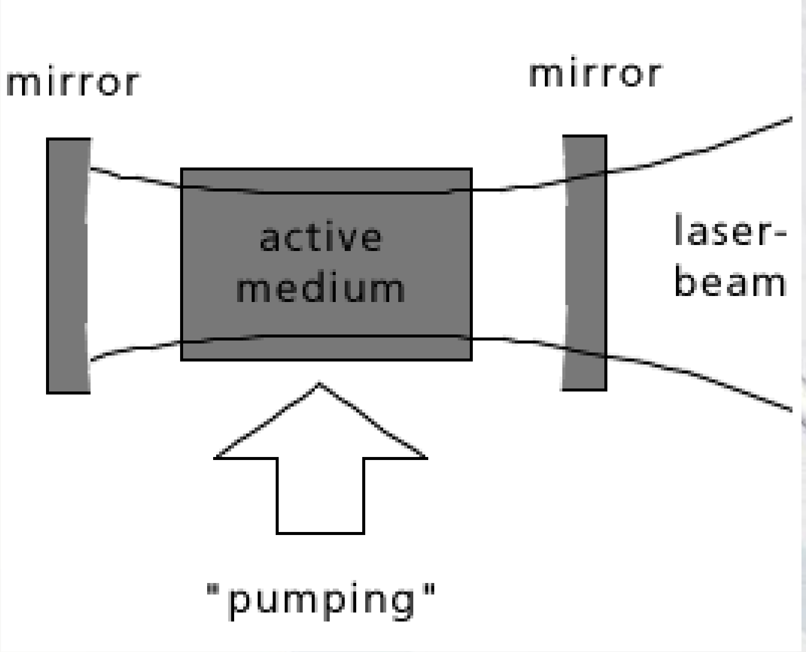
- Plasma arc cutting (also plasma arc machining, PAM) is mainly used for cutting thick sections of electrically conductive materials . A high-temperature plasma stream (up to 60,000° F) interacts with the work-piece, causing rapid melting. A typical plasma torch is constructed in such a way that the plasma is confined in a narrow column about 1 mm in diameter.

Plasma Beam Machining

- The electrically conductive work-piece is positively charged, and the electrode is negatively charged. Relatively large cutting speeds can be obtained: for example, 380 mm/min for a stainless steel plate 75 mm thick at an arc current of 800 A.
- Tolerances of ± 0.8 mm can be achieved in materials of thicknesses less than 25 mm, and tolerances of ± 3 mm are obtained for greater thicknesses.
- The HAZ for plasma arc cutting varies between 0.7 and 5 mm in thickness and the method is used primarily for ferrous and nonferrous metals.

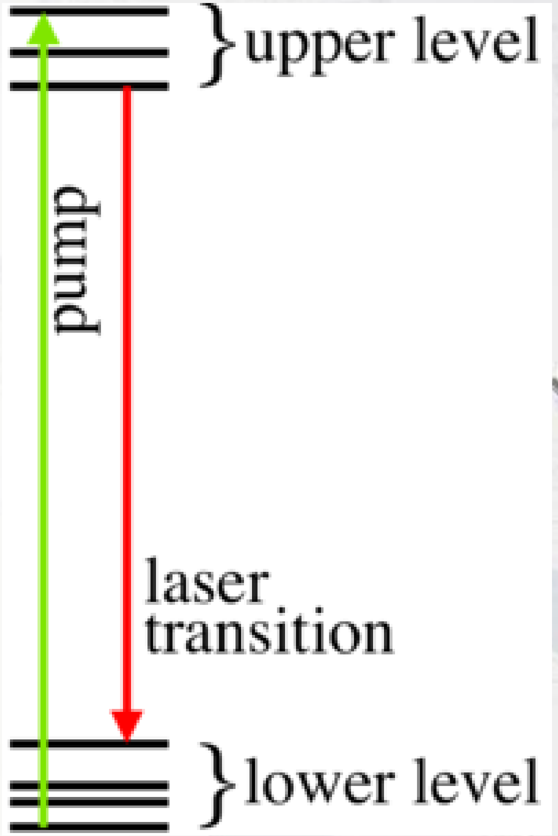
What is a laser?

- The word LASER is an acronym which stands for Light Amplification by Stimulated Emission of Radiation. It actually represents the principle itself but is nowadays also used to describe the source of the laser beam.
- The main components of a laser are the laser active, light amplifying medium and an optical resonator which usually consists of two mirrors.



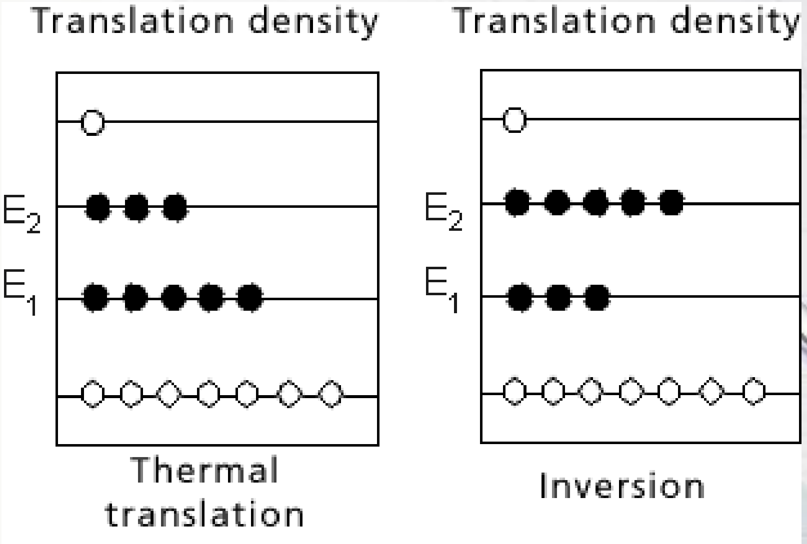
What is a laser?

- Laser Active Medium: Laser light is generated in the active medium of the laser. Energy is pumped into the active medium in an appropriate form and is partially transformed into radiation energy. The energy pumped into the active medium is usually highly entropic, i.e. very disorganised, while the resulting laser radiation is highly ordered and thus has lower entropy. Highly entropic energy is therefore converted into less entropic energy within the laser. Active laser media are available in all aggregate states:solid, liquid and gas.



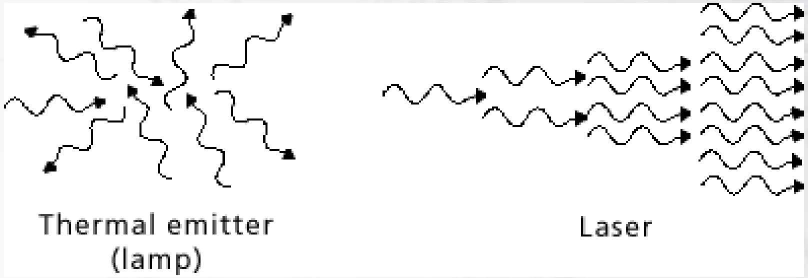
What is a laser?

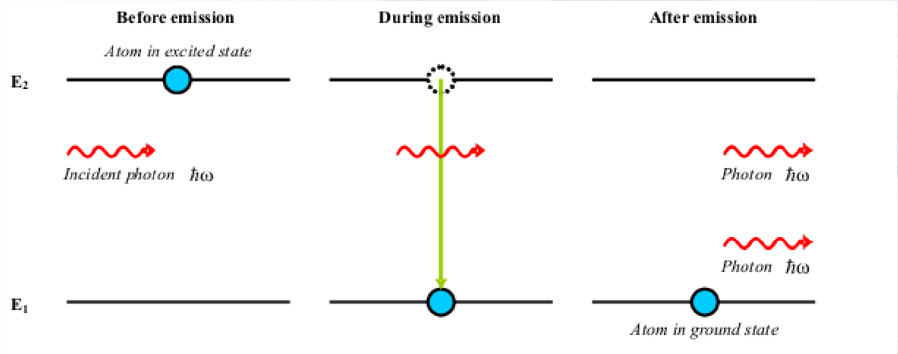
- Inversion:The laser transition of an active medium occurs between two defined levels or level groups - the upper (E2) and the lower (E1). Important in terms of laser operation is that an inverted condition is achieved between the two energy levels: the higher energy level must be more densely populated than the lower.
- Inversion is never achieved in systems in thermodynamic equilibrium. Thermal equilibrium is thus characterised by the fact that the lower energy level is always more densely populated than the higher. Lasers must therefore operate in opposite conditions to those which prevail in thermal equilibrium.



What is a laser?

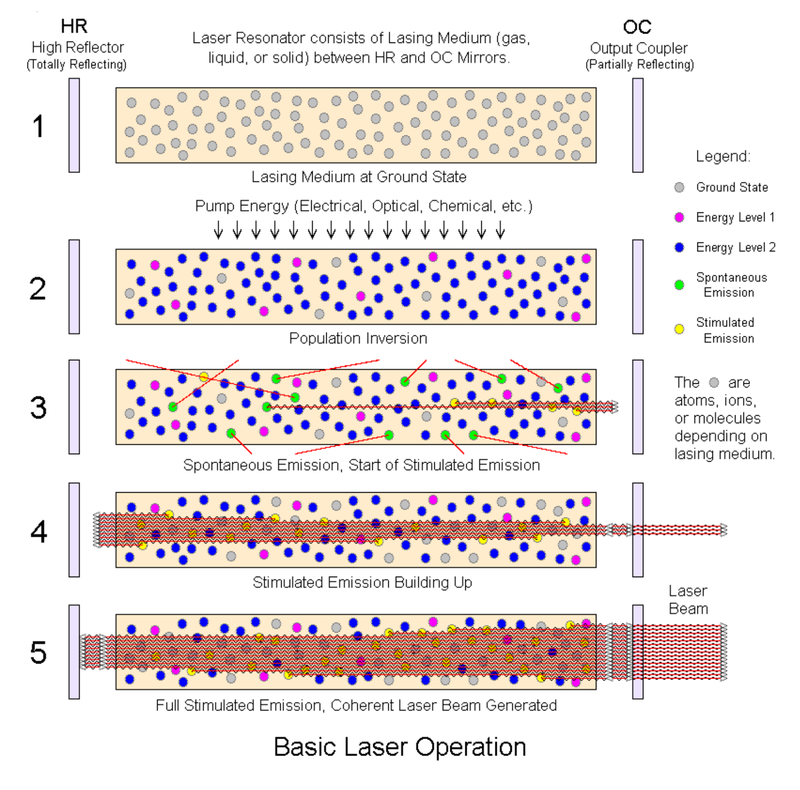
- Lasing principle: During spontaneous emission of photons, the quanta are emitted in a random direction at a random phase. In contrast, the atoms emitted during stimulated emission are forced into phase by the radiation field. When a number of these in-phase wave trains overlap each other, the resultant radiation field propagates in the one direction with a very stable amplitude.





What is a laser?

- Two conditions must be met in order to synchronise this stimulated atomic emission: firstly, there must be more atoms present in their higher, excited states than in the lower energy levels, i.e. there must be an inversion. This is necessary otherwise the stimulated emissions of quanta will be directly re-absorbed by the atoms which are present in lower energy states. The inverted condition does not prevail in nature: the lower energy levels are normally more densely populated than the higher levels. Some means of 'pumping' the atoms is therefore needed. .



What is a laser?

- Laser pumping is the act of energy transfer from an external source into the gain medium of a laser. The energy is absorbed in the medium, producing excited states in its atoms. When the number of particles in one excited state exceeds the number of particles in the ground state or a less-excited state, population inversion is achieved. In this condition, the mechanism of stimulated emission can take place and the medium can act as a laser or an optical amplifier. The pump power must be higher than the lasing threshold of the laser.
- The pump energy is usually provided in the form of light or electric current, but more exotic sources have been used, such as chemical or nuclear reactions.