Laser Surface Modification

PG 1st Year-Second Semester

School of Laser Science and Engineering

Laser Surface Heat Treatment

- Laser surface modification is used to change either the surface composition or the microstructure of a material to give it certain desired properties.
- This may involve hardening the surface to increase its resistance to wear, or inducing compressive residual stresses in the surface layers to enhance fatigue life.
- Hardness, friction, fatigue and resistance to wear, corrosion can be increased.

Laser surface modification

- Laser surface heat treatment → no melting takes place
- Laser surface melting → a thin surface layer of the workpiece is melted
- Laser direct metal deposition (cladding, alloying, and hard coating) → second material is applied to the surface and melted by the laser beam to bond to the surface.
- Laser physical vapor deposition → second material is applied in vapor form, and no melting
- Laser shock peening → generates shock waves, which induce compressive residual stresses on the surface

Laser Surface Heat Treatment

1. Working Principle
2. Important Criteria
3. Key Process Parameters
4. Temperature Field
5. Microstructural Changes in Steels
6. Nonferrous Alloys
7. Hardness Variation
8. Residual Stresses
9. Advantages and Disadvantages of Laser Surface Treatment

Laser Surface Heat Treatment

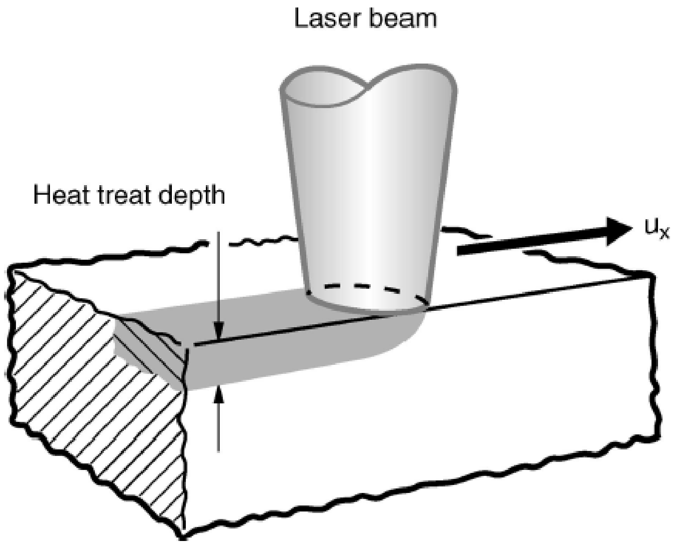
1. **Working Principle**

- Surface heat treatment normally involves exposing the surface of a material to a thermal cycle of rapid heating and cooling such that the surface layers in the case of steels, for example, are first austenitized (**400°C to 800°C)**, and then quenched, to induce martensitic transformation.

- Heating and cooling rates depend on thermal conductivity and thickness of material, laser power, beam size and traverse rate.

- The process does not involve melting, and the transformations occur in the solid state.

- Laser heat treating, also known as laser hardening, is a surface modification process used to increase wear resistance or extend the lifetime for items ranging from household tools to parts in automobile manufacturing and tooling in heavy industry and transport sectors. Laser hardening is most commonly used for steel and cast iron materials. Lasers transform target areas on metal parts by controlled localized heating while preserving the metallurgical properties of the base material.



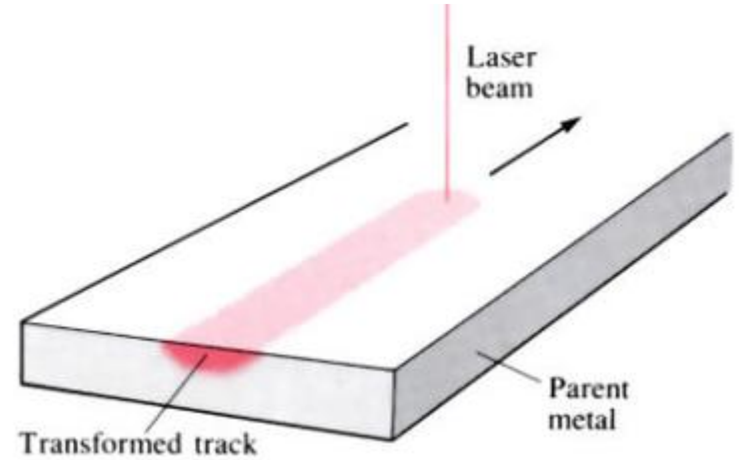
Laser Surface Heat Treatment

1. **Working Principle**

The cooling rates for laser heat treatment can be as high as 10^7°C/s (compare with cooling rates of about 300°C/s for arc welding) and produce relatively short austenite cycles (in the order of 0.01–1.0 s).

The essential steps involved in laser hardening

- ✓ *Cleaning*
- ✓ *Coating*
- ✓ *Hardening*
- ✓ *Tempering*
- ✓ *Inspection*



Laser Surface Heat Treatment

2. Important Criteria

1. For steels, the region to be hardened needs to be heated well into the austenite temperature range, and be maintained in that temperature range long enough for carbon diffusion to occur.

- ✓ **Diffusion** is a process used in manufacturing that increases the hardness of steels. In diffusion hardening, diffusion occurs between a steel with a low carbon content and a carbon-rich environment to increase the carbon content of the steel and ultimately harden the workpiece.
- ✓ Diffusion only happens through a small thickness of a piece of steel (about 2.5 µm to 1.5 mm), so only the surface is hardened while the core maintains its original mechanical properties.

2. There must be adequate mass in contact with the region to be hardened to permit self-quenching by conduction into the bulk material.

Laser Surface Heat Treatment

3. Key Process Parameters

- ❑ Beam power, scanning speed, beam size and shielding gas.
- ❑ Beam mode.
- ❑ Beam absorption by the workpiece.
- ❑ Workpiece material properties and initial microstructure.

The process outputs:

✓Hardness

✓Depth of the hardened region

✓Microstructure

✓Induced residual stresses

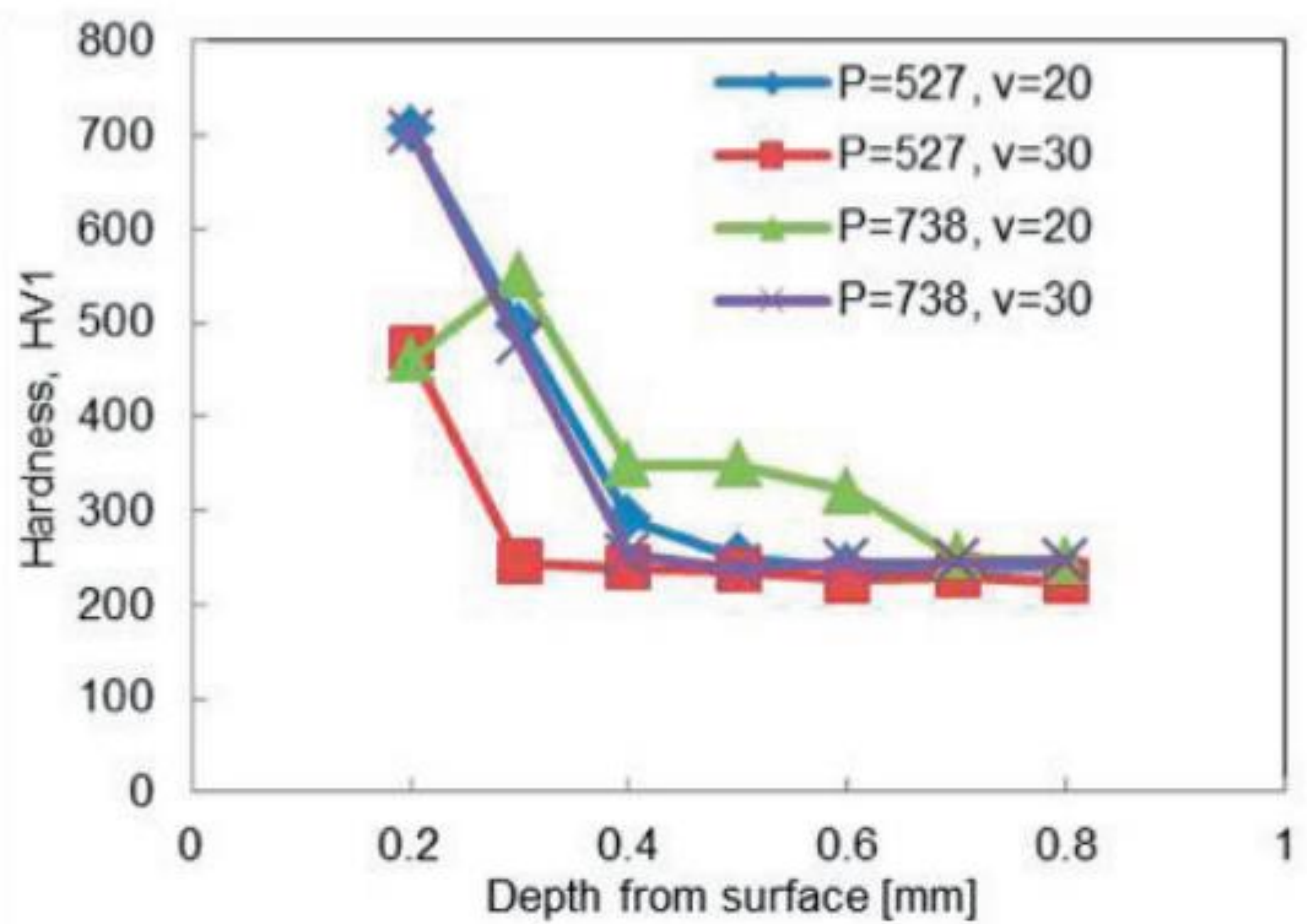
Typical Laser Heat Treatment Process Parameters

Parameters	Values	Units
Power	0.5–9	kW
Defocused beam diameter	2–20	mm
Power densities	1–100	kW/cm^2
Scanning velocities	5–400	mm/s
Hardened depths	0.2–2.5	mm

Laser Surface Heat Treatment

3. Key Process Parameters

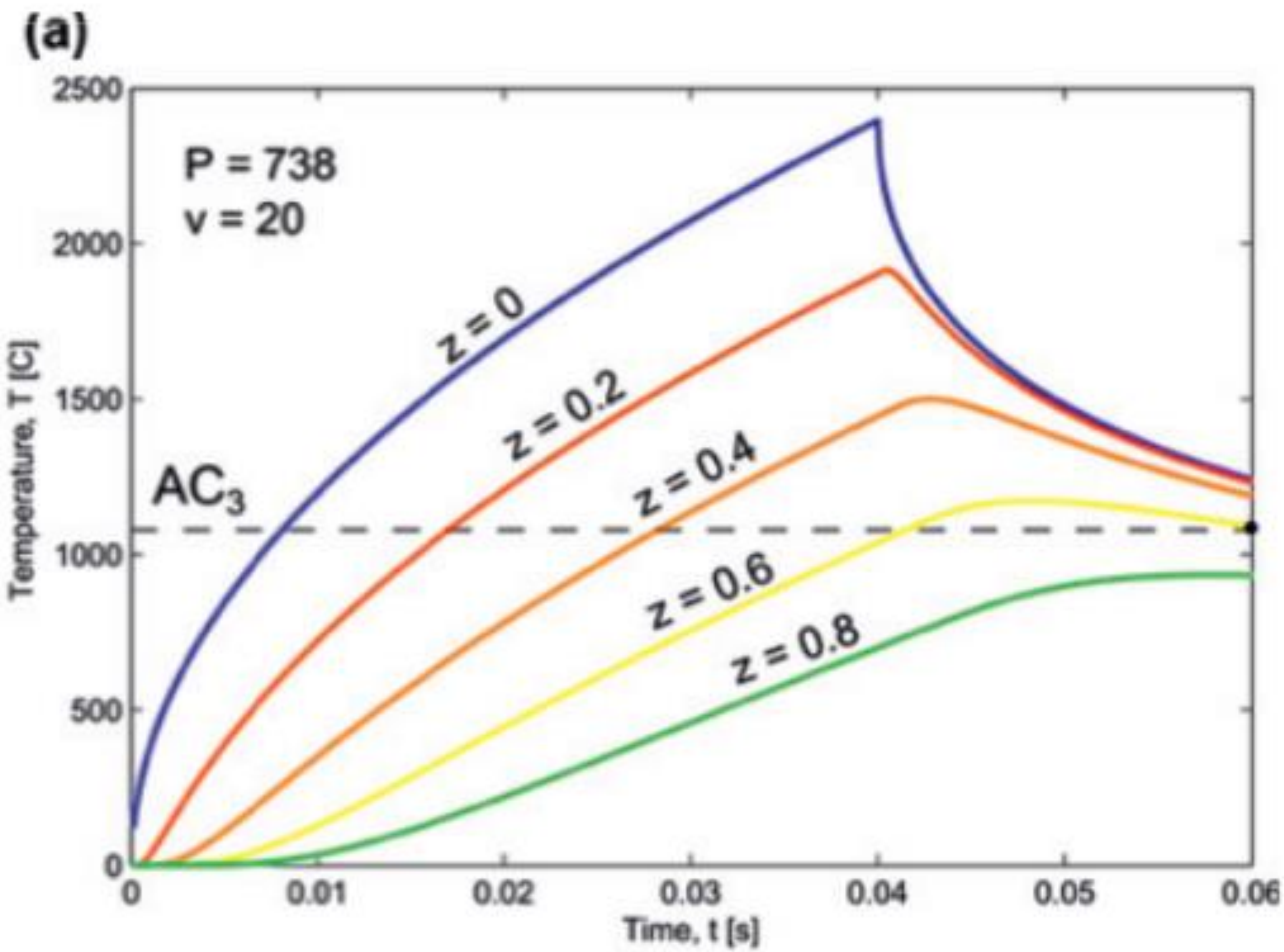
Beam power and scanning speed



Laser Surface Heat Treatment

3. Key Process Parameters

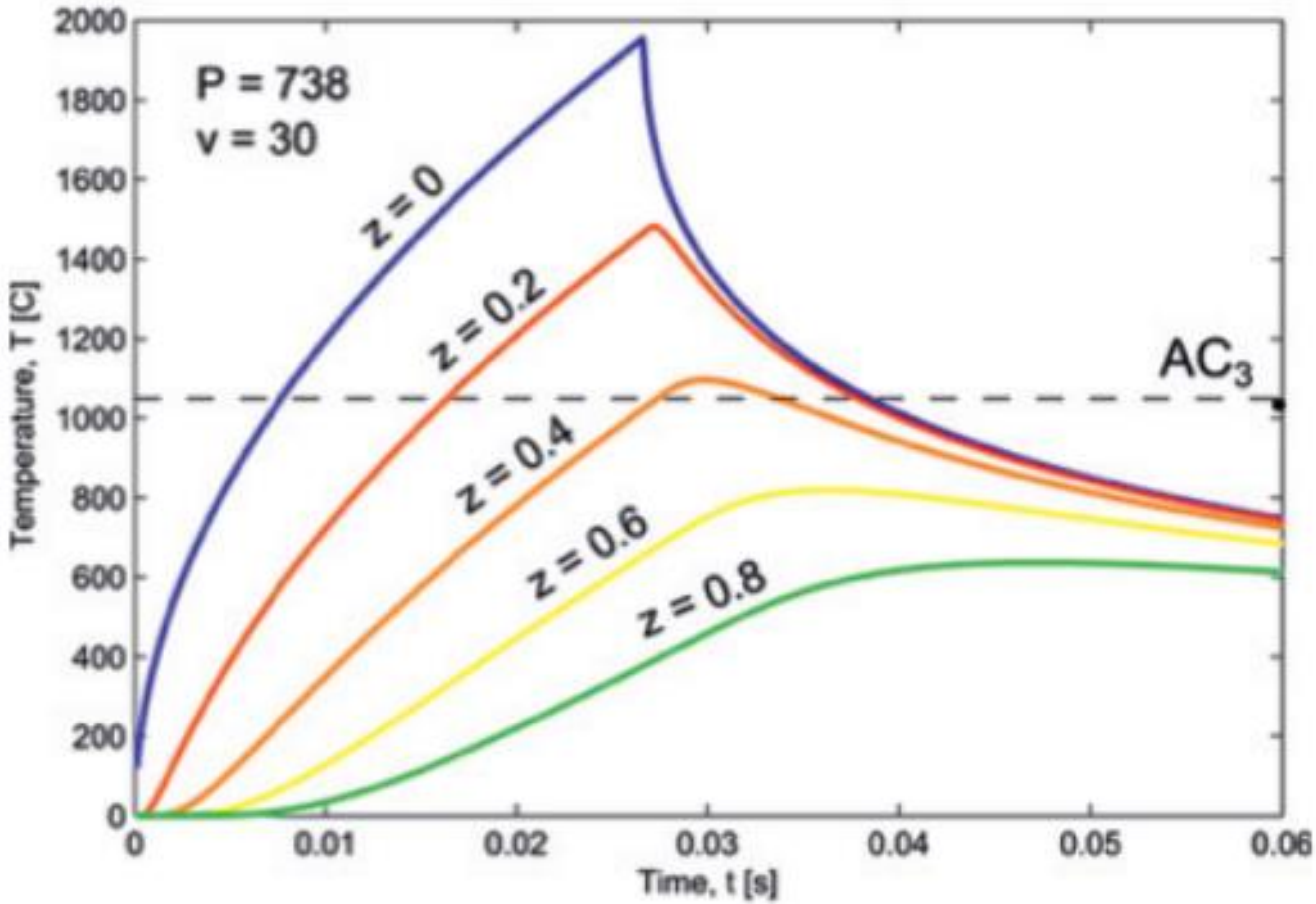
Beam power and scanning speed



Laser Surface Heat Treatment

3. Key Process Parameters

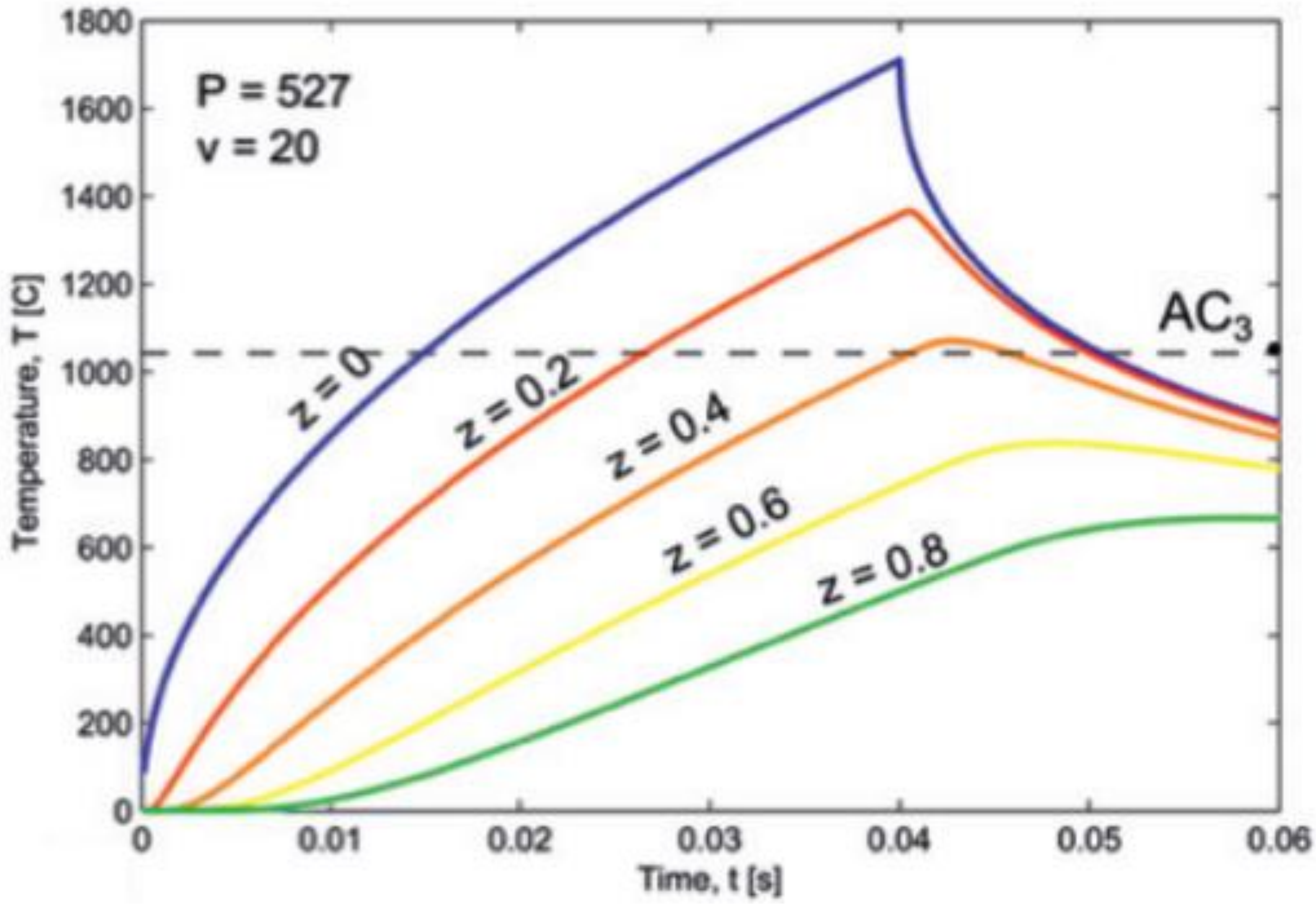
Beam power and scanning speed



Laser Surface Heat Treatment

3. Key Process Parameters

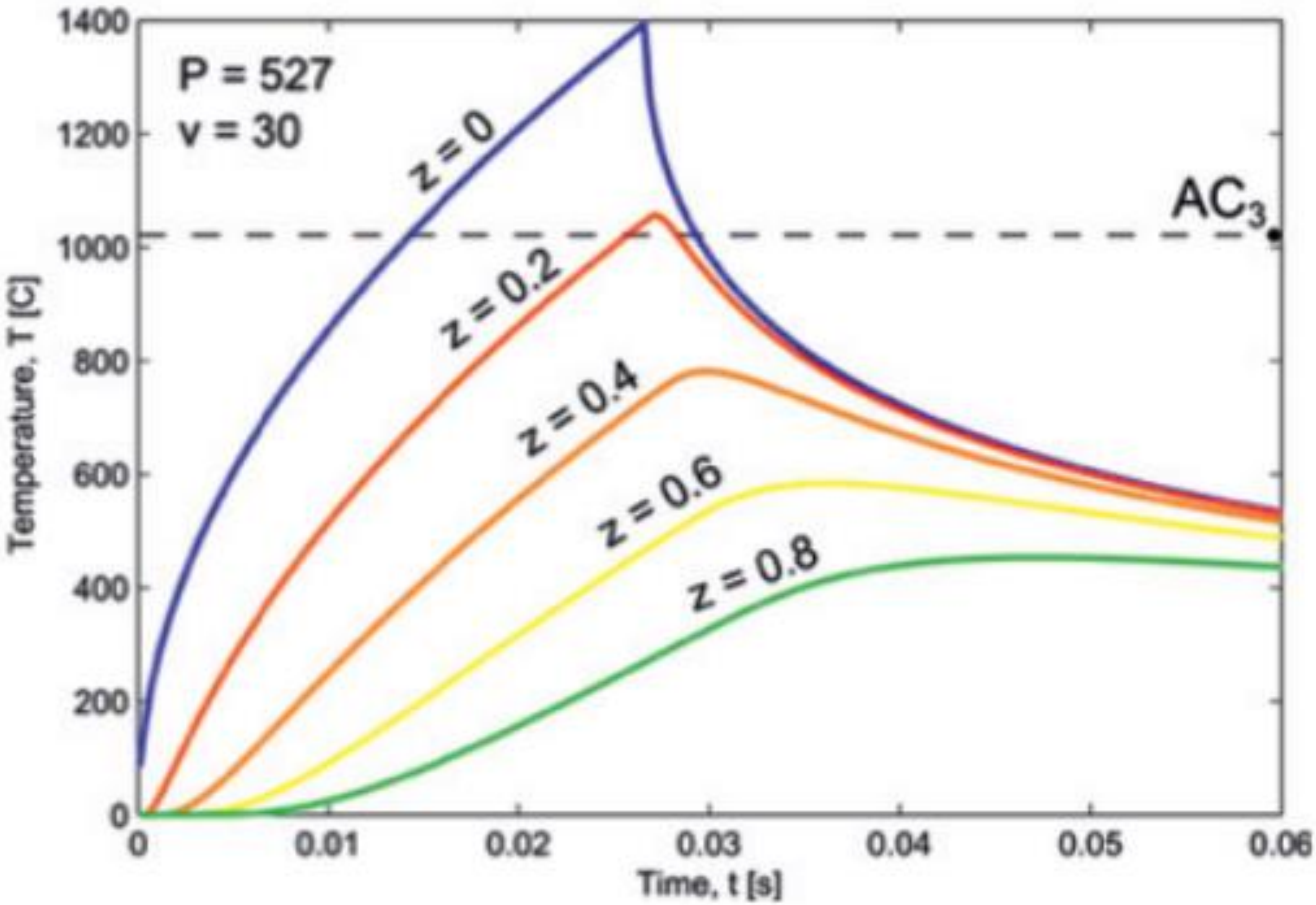
Beam power and scanning speed



Laser Surface Heat Treatment

3. Key Process Parameters

Beam power and scanning speed

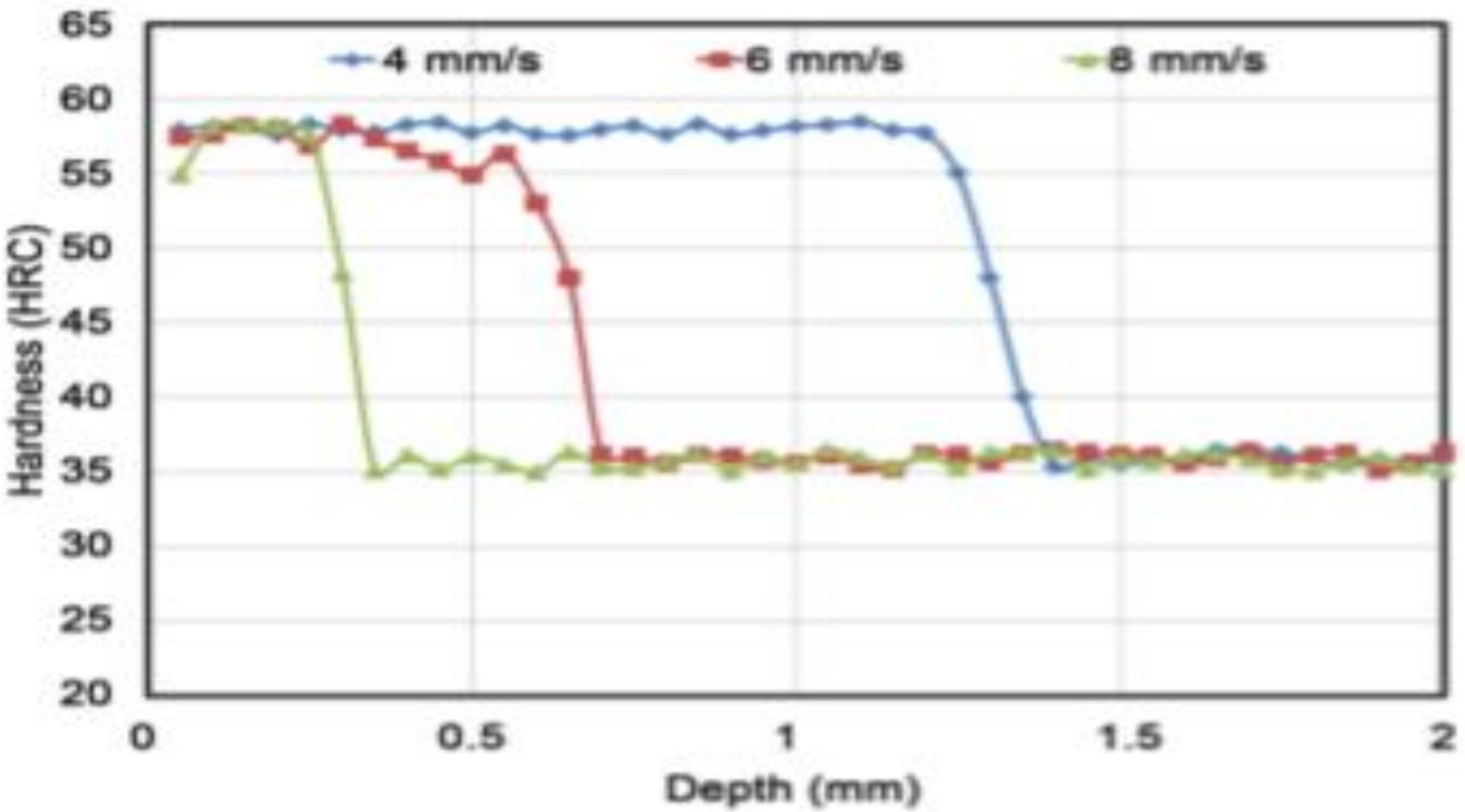


Laser Surface Heat Treatment

3. Key Process Parameters

Beam power and scanning speed

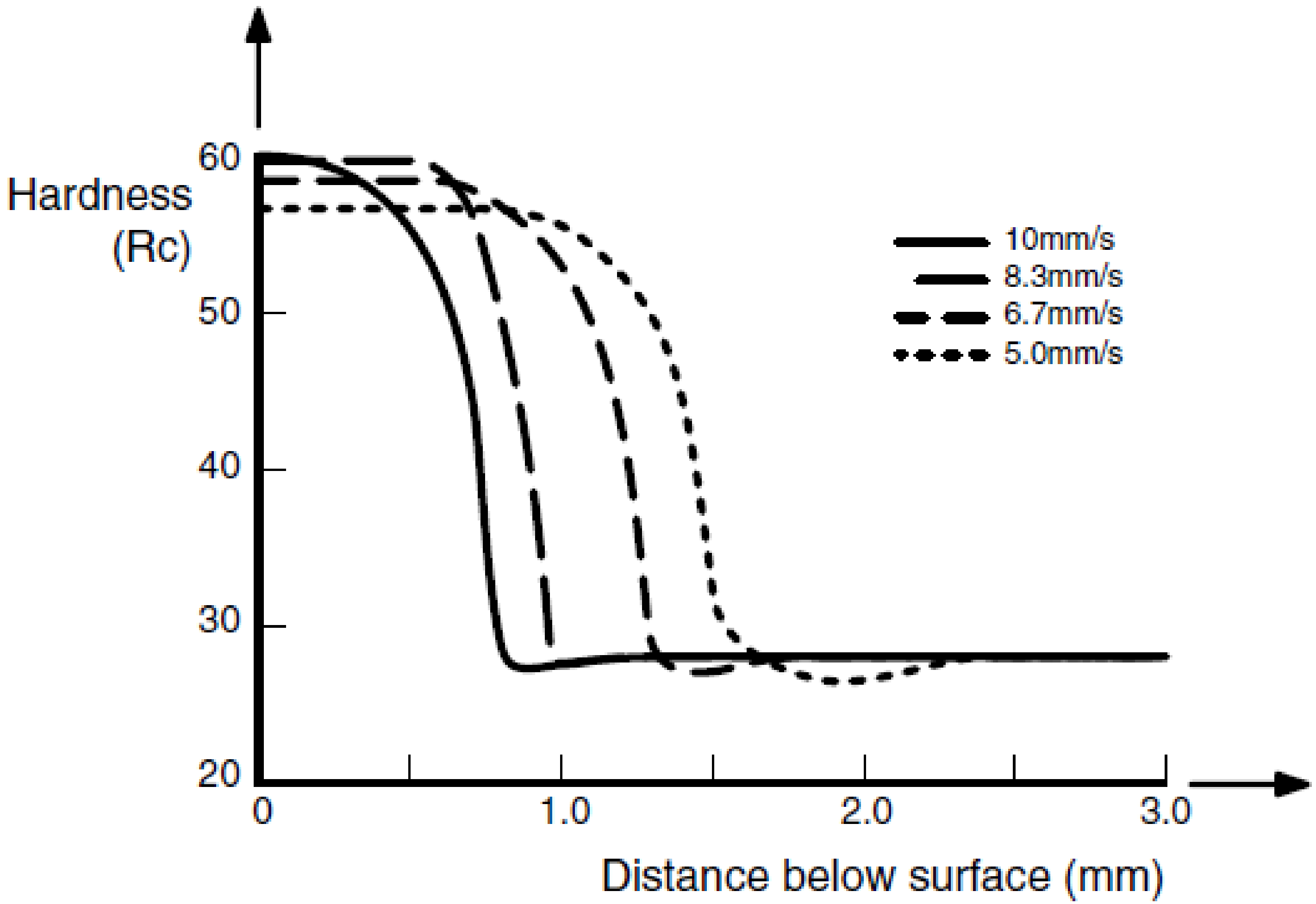
This is because reducing the scanning velocity increases the surface temperature and the reaction time for phase transformation(austenite), resulting in a larger average austenite grain size.



Laser Surface Heat Treatment

3. Key Process Parameters

Beam power and scanning speed

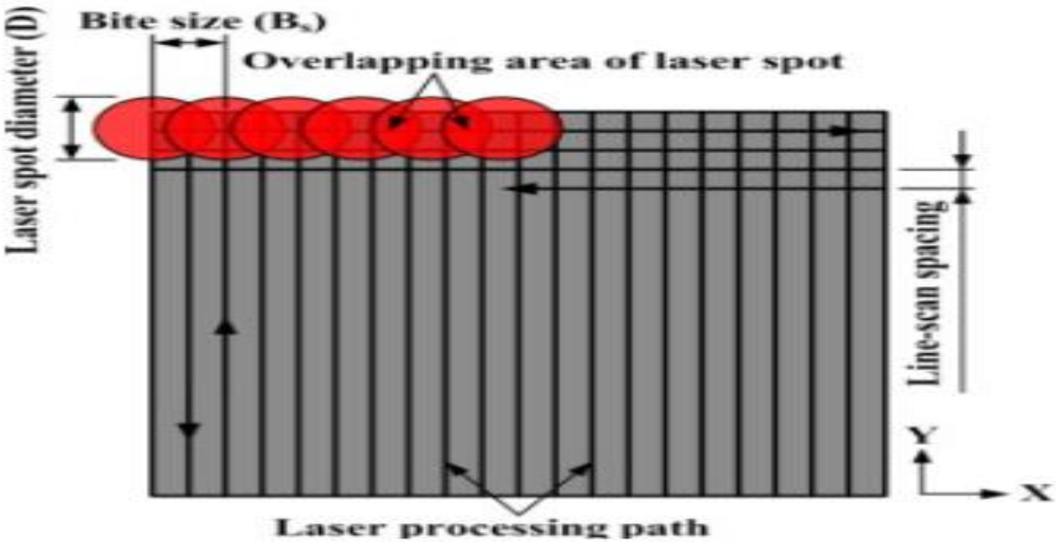


Laser Surface Heat Treatment

3. Key Process Parameters

Beam diameter

- Due to the relatively small size of the laser beam, it is necessary to scan the surface a number of times, with the beam being shifted a specific amount for each scan.
- To ensure that the entire area of interest is treated, there has to be some amount of overlap between the scans. However, the overlap may anneal portions of the previously hardened structure.
- While such annealing may not significantly affect the wear properties of a material, it could have significant impact on the fatigue properties, with the softened regions providing preferential sites of stress relaxation at the surface.



Laser Surface Heat Treatment

3. Key Process Parameters

Shielding gas

Shielding gas (usually argon or helium) may be used to protect the surface from oxidation with flow rates similar to those used during laser welding, about 10 L/min.

Due to its higher thermal conductivity, helium results in higher hardness

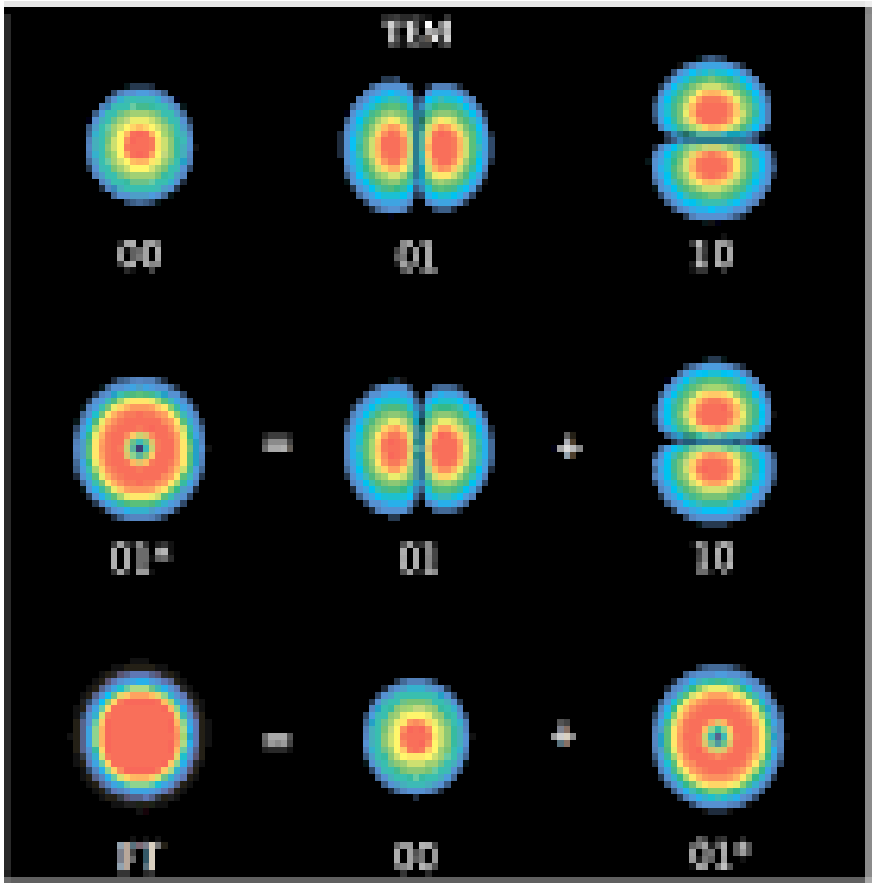
	Thermal Conductivity at 300 K (W/mK)
Air	0.026
Ar	0.018
CO	0.025
CO_2	0.017
H	0.182
He	0.151
N2	0.026
Ne	0.049
O_2	0.027

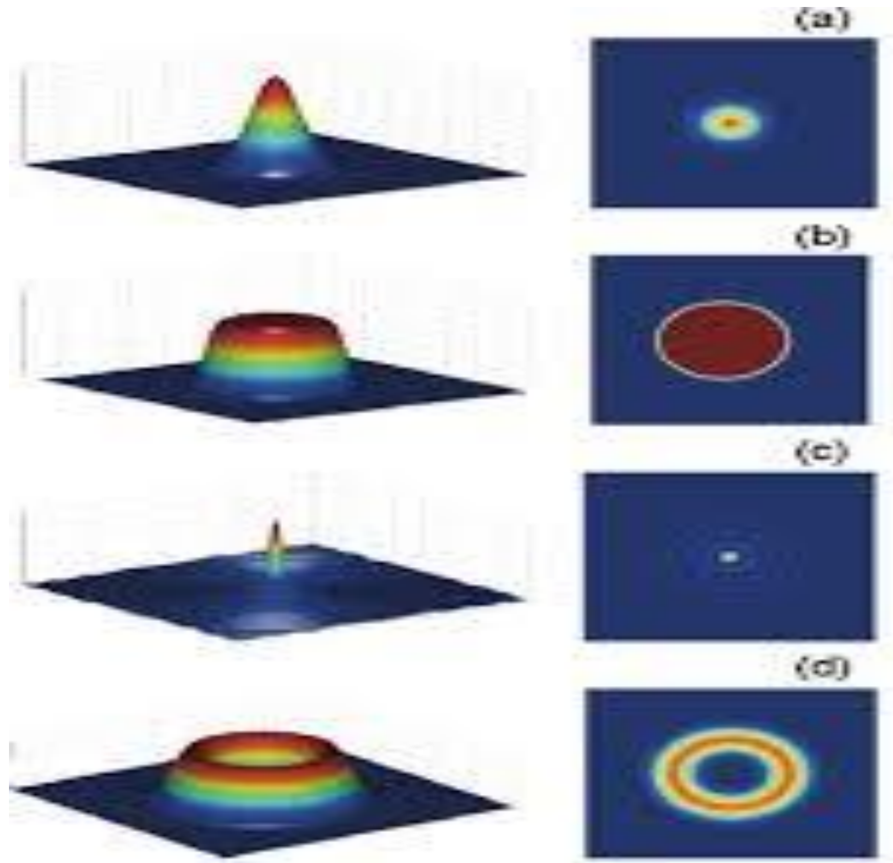
Laser Surface Heat Treatment

3. Key Process Parameters

Beam mode

- ❑ Gaussian mode are not particularly suitable for laser surface treatment .
- ❑ A relatively wide and uniformly distributed beam is required to obtain uniform surface heating over a wide area and thus avoid localized surface melting.





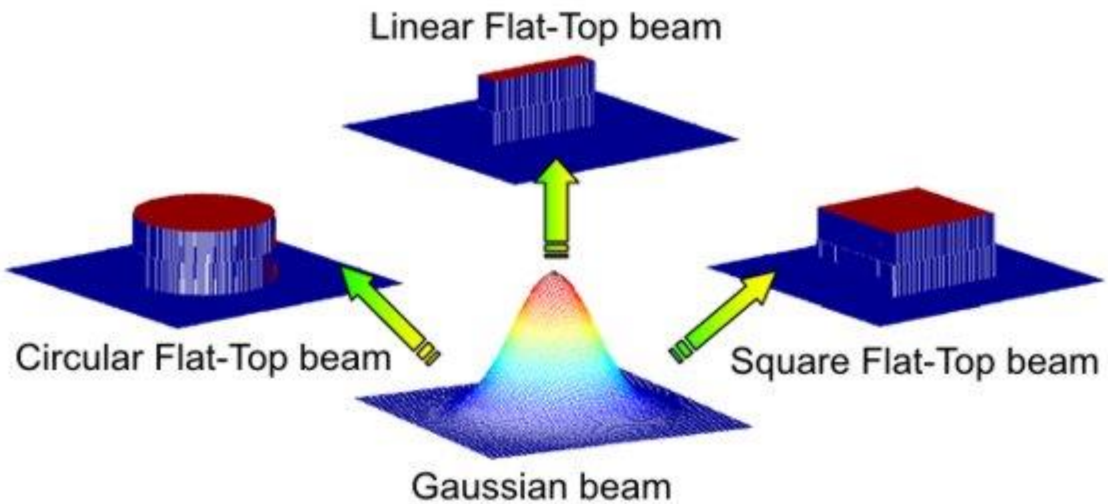
Laser Surface Heat Treatment

3. Key Process Parameters

Beam mode

Beam-shaping techniques

1. Beam defocusing using a lens.
2. Optical integration.
3. Beam rastering or scanning.
4. Kaleidoscope or light pipe.



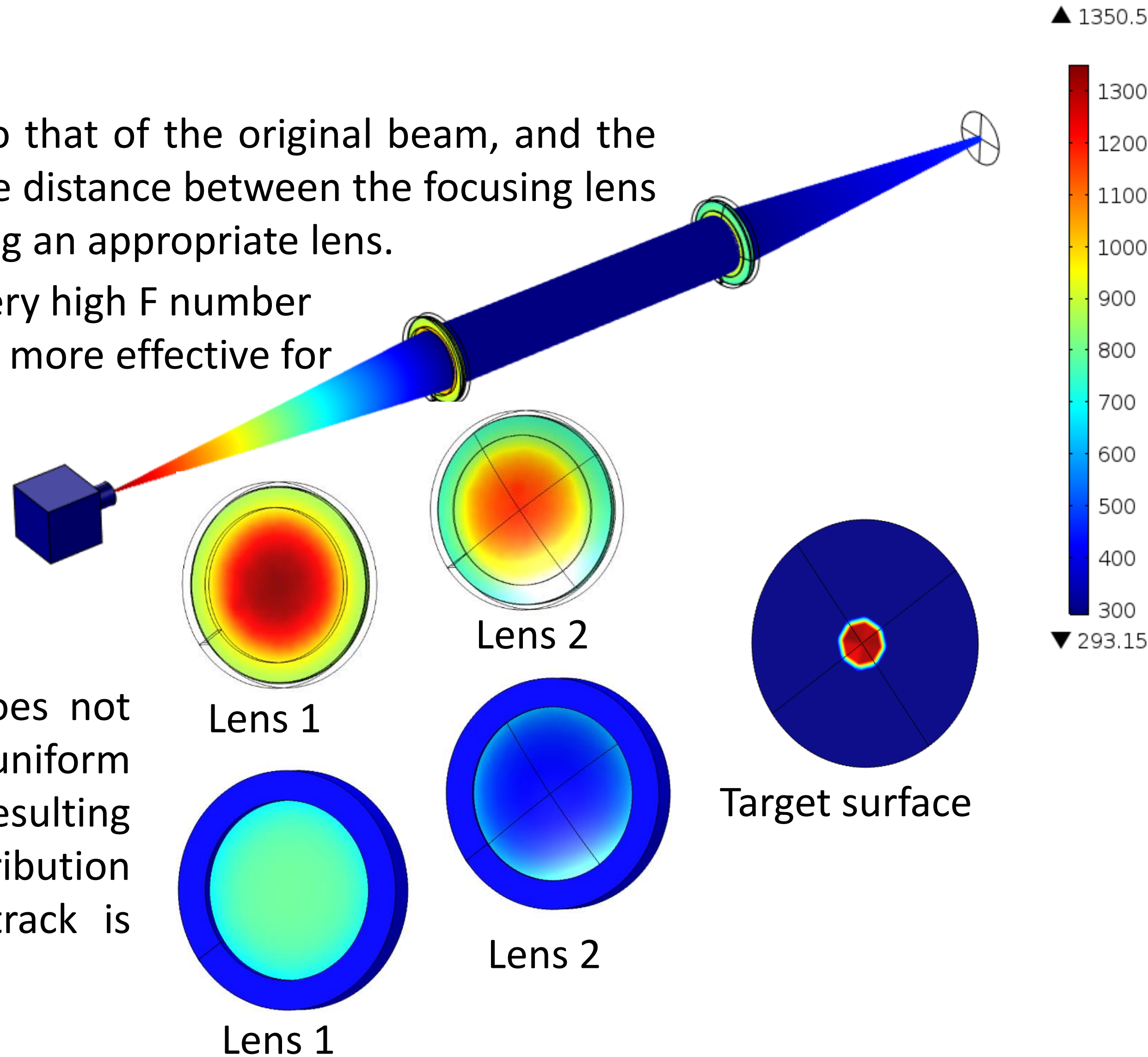
Laser Surface Heat Treatment

3. Key Process Parameters

Beam mode

Beam defocusing using a lens

- The beam shape is similar to that of the original beam, and the size is changed by varying the distance between the focusing lens and the workpiece or by using an appropriate lens.
  - A focusing system with a very high F number or long focal length may be more effective for this method
  - F number is the ratio of the focal length of a lens to its diameter
  - Since beam defocusing does not necessarily produce a uniform beam distribution, the resulting penetration depth distribution across the heat-treated track is also nonuniform.

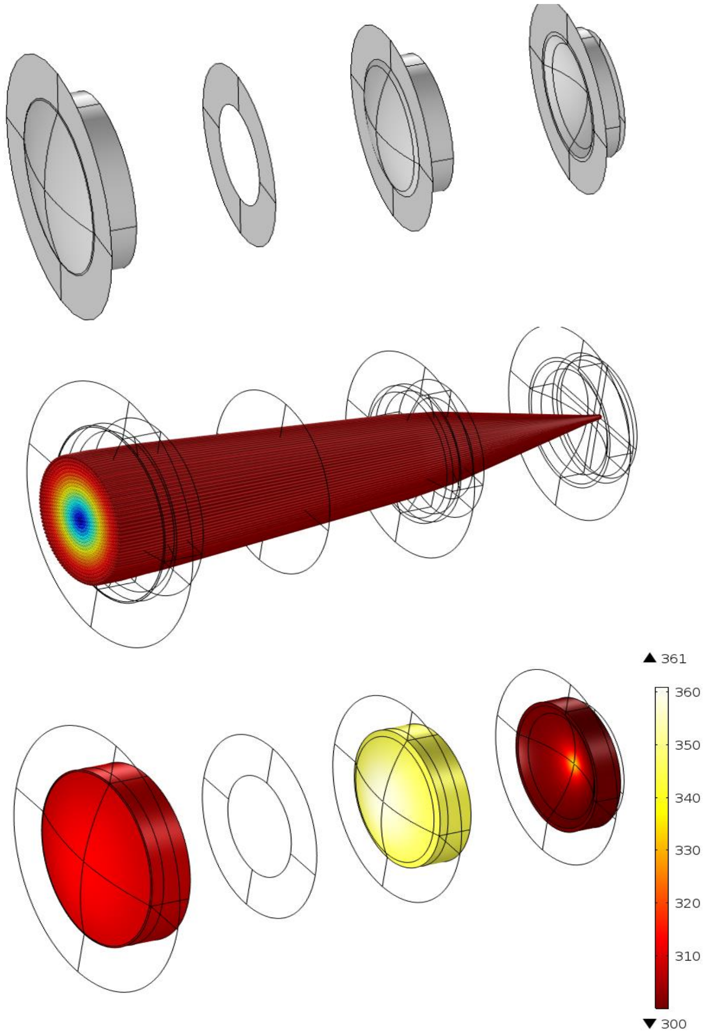


Laser Surface Heat Treatment

3. Key Process Parameters

Beam mode

- Only about 20–30% of the track width may be of uniform penetration depth, depending on the original beam mode.
- Since the focusing lens is normally part of the beam delivery system, this method is the easiest to implement.
- It requires no additional effort or expense.



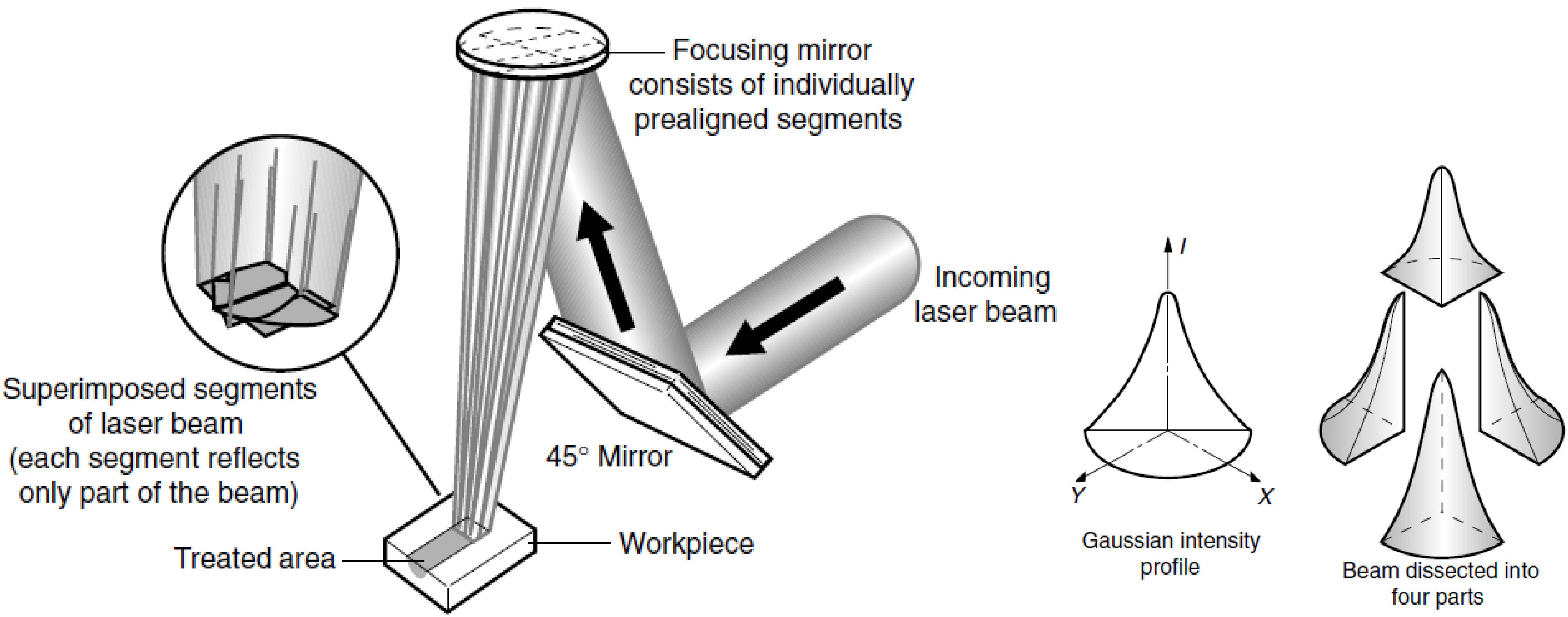
Laser Surface Heat Treatment

3. Key Process Parameters

Optical Integration

Optical integration involves segmenting the beam into a large number of portions and superposing the individual segments on the same focal plane using a beam integrator.

A beam integrator has a number of small mirror segments mounted on a base plate, that is, a multifaceted mirror.



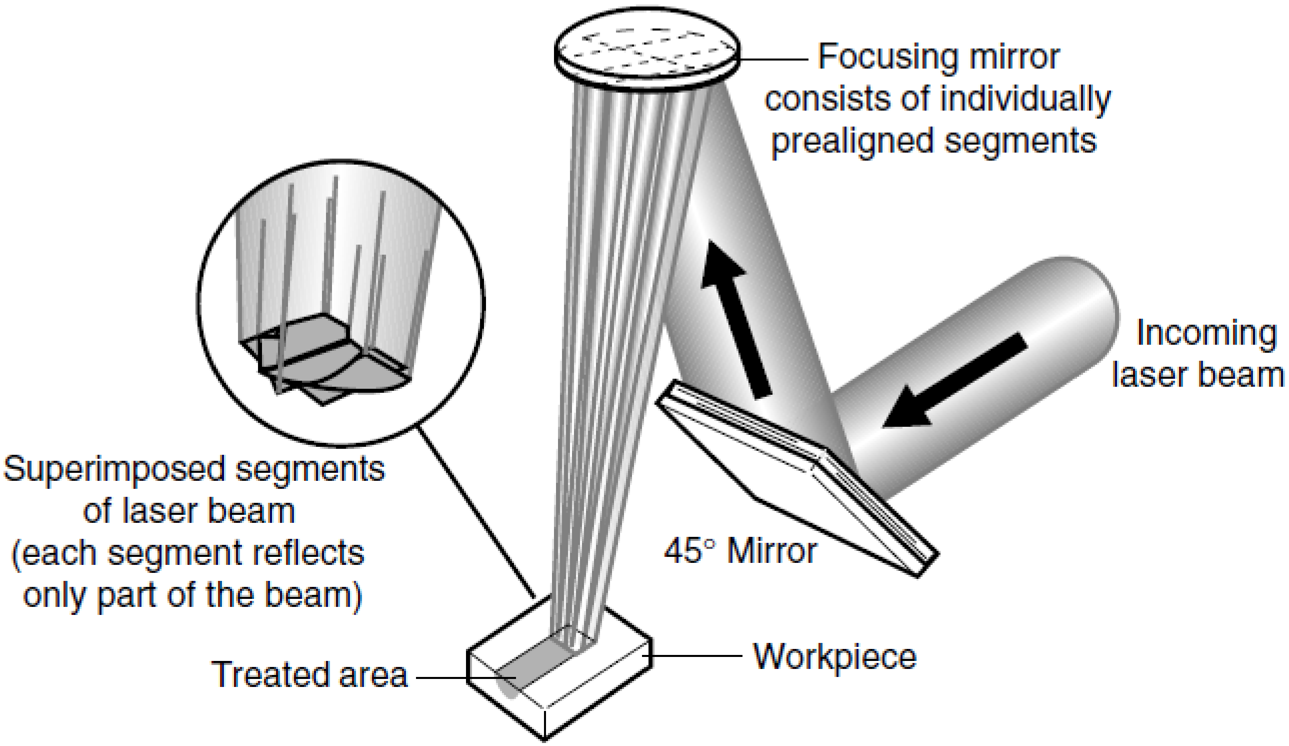
Laser Surface Heat Treatment

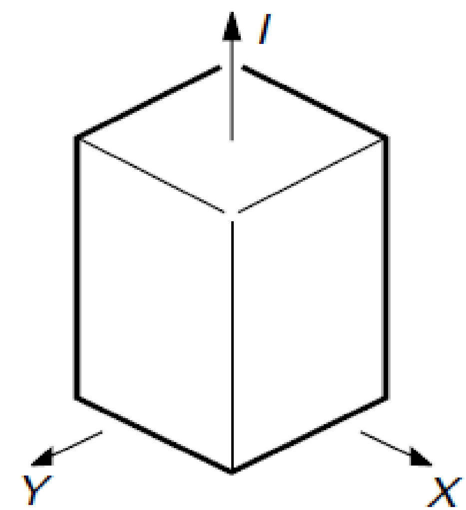
3. Key Process Parameters

Optical Integration

Contiguous mirror segments are positioned to be in close contact with each other to minimize beam loss between the segments.

Two of the segmented beams are of one orientation, while the other two are of opposite orientation, resulting in near-perfect intensity averaging.





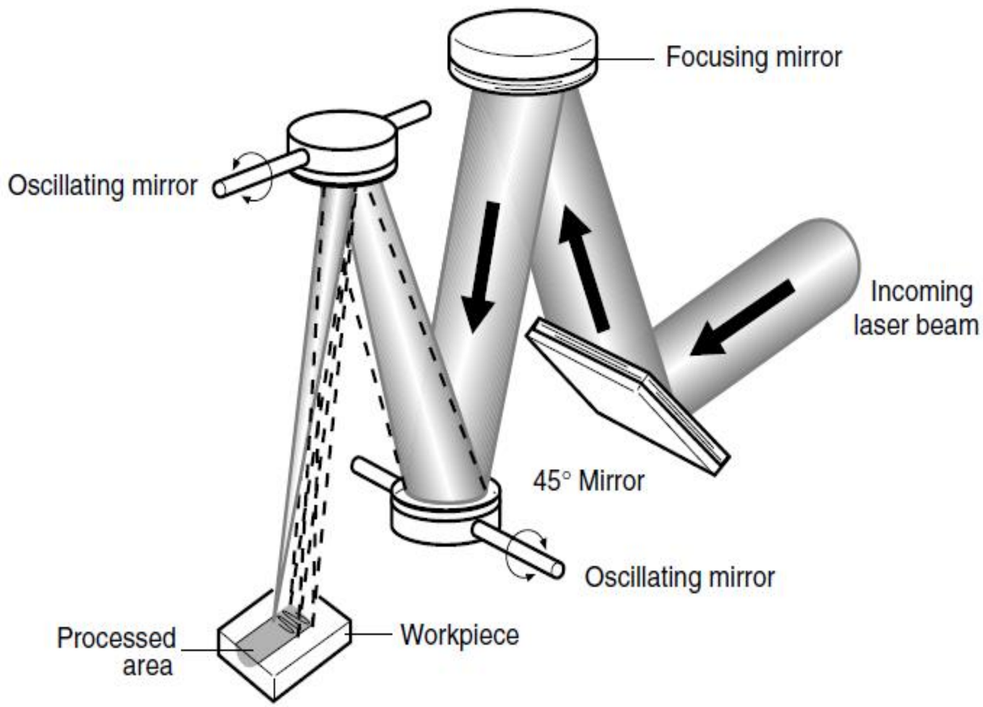
Uniform intensity profile

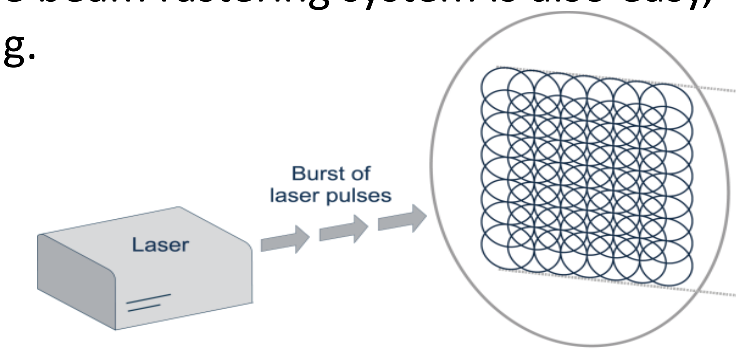
Laser Surface Heat Treatment

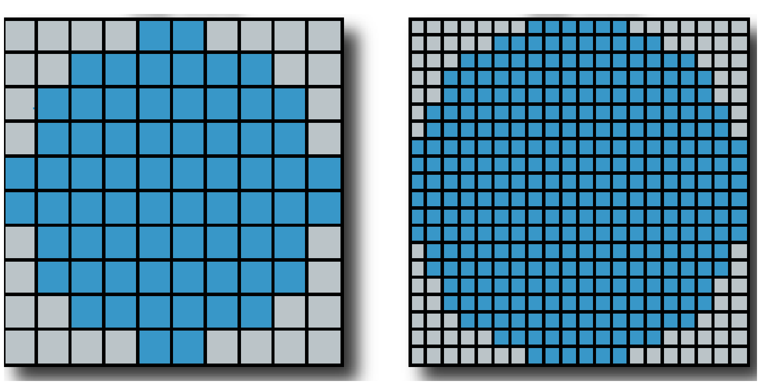
3. Key Process Parameters

Beam Rastering or Scanning

- A uniformly distributed beam can also be achieved by rastering a finely focused beam to cover a wide area.
- The process involves vibrating two mirrors to get the beam to move back and forth at a high frequency to create the required pattern.
- Like the optical integration system, installation of the beam rastering system is also easy, but again requires more effort than beam defocusing.





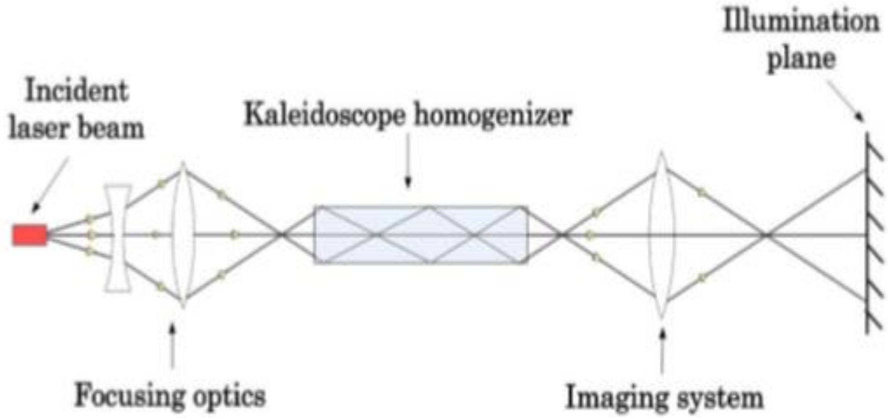


Laser Surface Heat Treatment

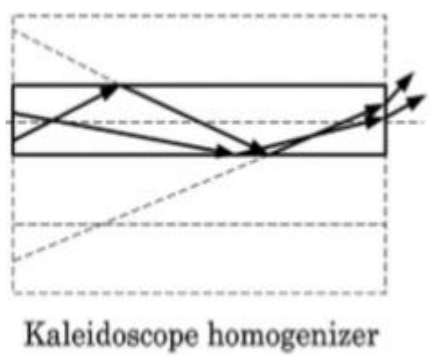
3. Key Process Parameters

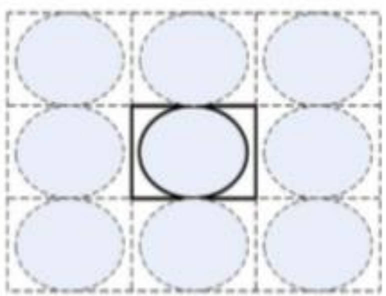
Kaleidoscope or Light Pipe

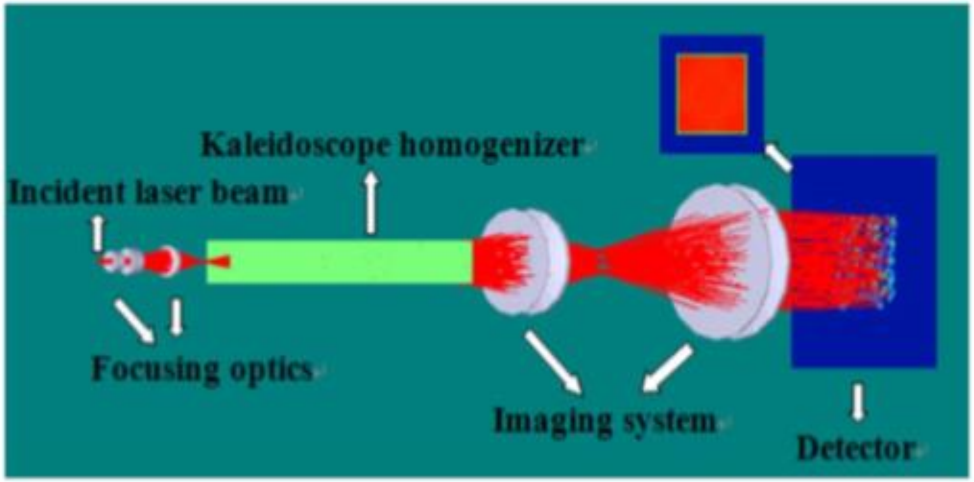
When the incident light goes into a kaleidoscope, the light intensity distribution on the output surface is superposed by all the virtual images after multiple reflections. Each virtual image is corresponding to a different space solid angle of the light, and therefore this leads to different energy distributions.



The light intensity distribution on the output surface consists of a lot of rays, and that makes the beam intensity distribution uniform







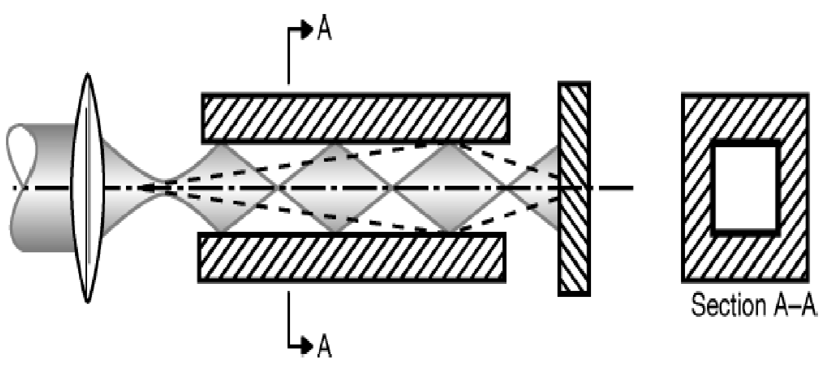
Laser Surface Heat Treatment

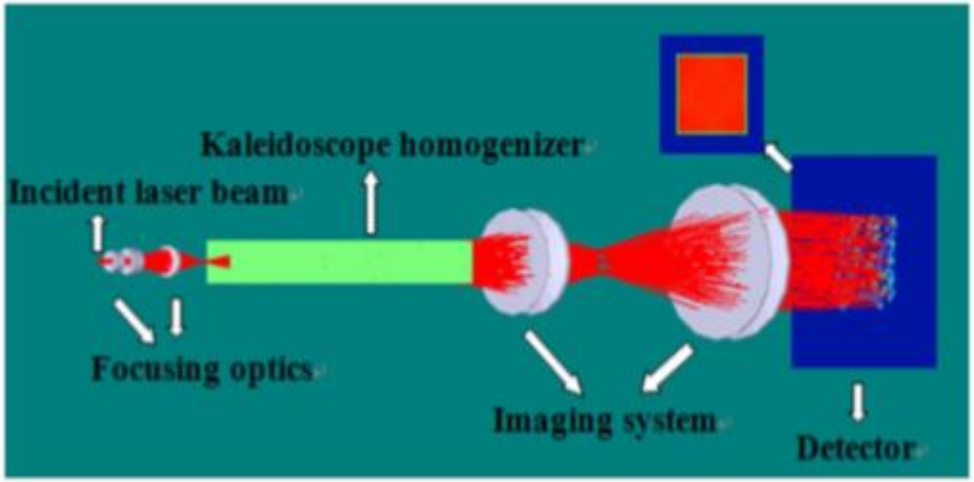
3. Key Process Parameters

Kaleidoscope or Light Pipe

For an incident beam with circular symmetry, the more virtual images generated in the kaleidoscope, the better the homogenizing results might be achieved. It is because different virtual images correspond to different space solid angles of the light beam, and the intensity distribution is more evenly assigned to each virtual image.

Theoretically, for a particular end face shape kaleidoscope, the bigger the size ratio between longitudinal length and end face width, the better the homogenizing results we would achieve. At this point, there are more virtual images, therefore the output light intensity distributed on the output end surface is more uniform.





Laser Surface Heat Treatment

3. Key Process Parameters

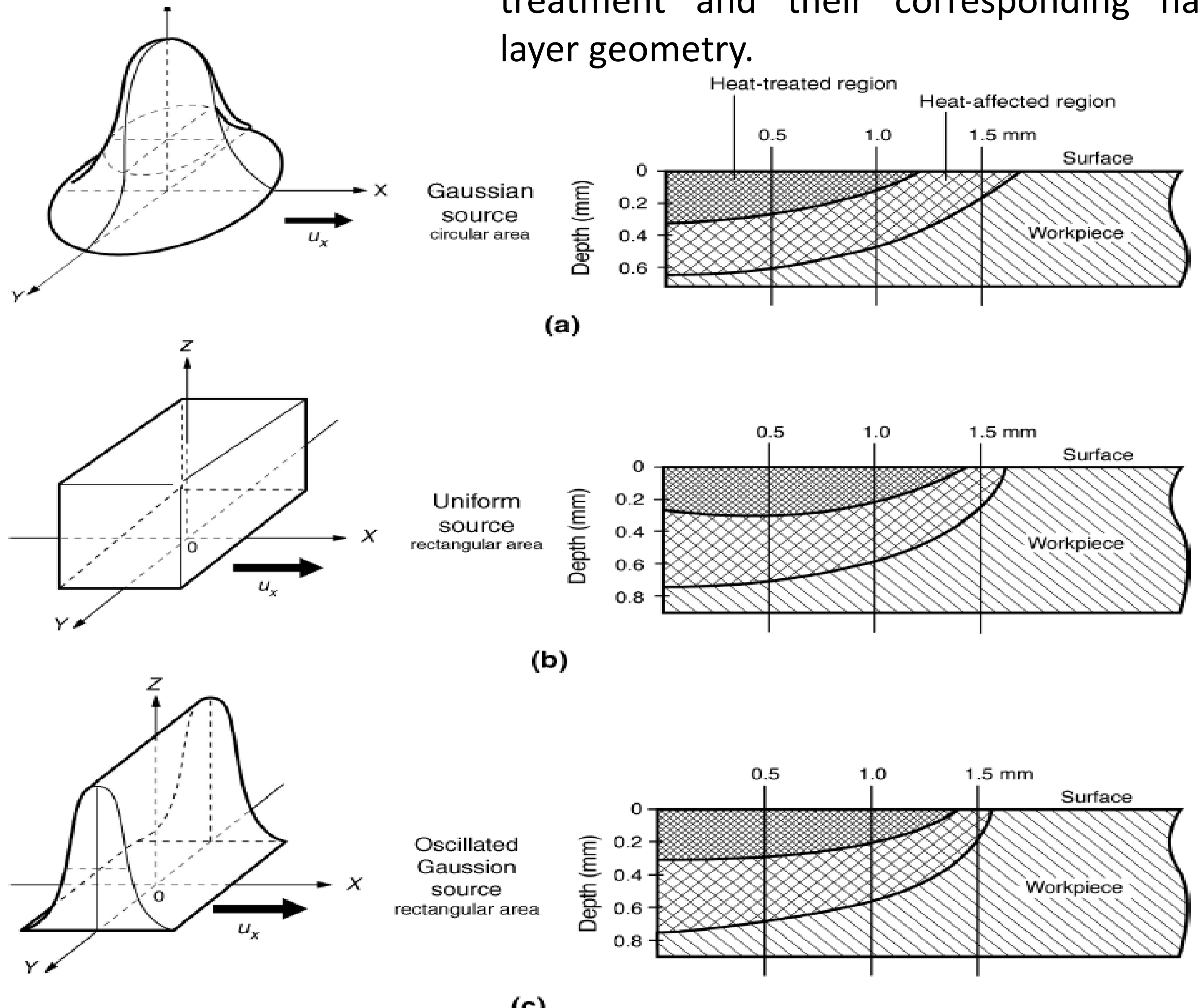
Comparison of the Four Beam-Shaping Devices

	Focusing Lens	Integration	Kaleidoscope	Beam Rastering
Power Loss	Lowest (1–2%)	Moderate (7–8%)	High (18–20%)	Low (4–6%)
Energy Uniformity	Good	Better	Better	Variable
Cost	Moderate	High	Low	High
Penetration	High	Moderate	Moderate	Variable
Penetration Uniformity	Uneven (20–30%)	Even (60–70%)	Even (45–50%)	Even
Limitations	Fragility of lens	Device length, Fragility	Needs to be close to workpiece	Scan rate might limit travel speed
Installation	Very easy	Easy	Easy	Easy
Applications	All applications	Heat treating, cladding, alloying	Heat treating only	Heat treating cladding, alloying

Laser Surface Heat Treatment

3. Key Process Parameters

Common beam shapes used in laser surface treatment and their corresponding hardened layer geometry.



(a) Circular or elliptical pattern Gaussian beam

(b) Rectangular beam

(c) Rectangular pattern Gaussian beam

Laser Surface Heat Treatment

3. Key Process Parameters

Beam Absorption

1. Absorption of the beam, which depends on the beam wavelength.
2. Angle of incidence.
3. Material properties or core microstructure.
4. Workpiece surface conditions (finish, coating, and so on)

Absorption of the beam

Normally, the wavelength decrease, the heating effect increase, because the material have more absorption for shorter wavelength radiation, especially for ultraviolet radiation.

1. Applying a thin layer of a highly absorbing coating to the material surface.
2. Using a linearly polarized laser beam on an uncoated surface.
3. Preheating the workpiece, since absorptivity increases with temperature.
4. Changing the composition of the material surface by oxidation before processing.

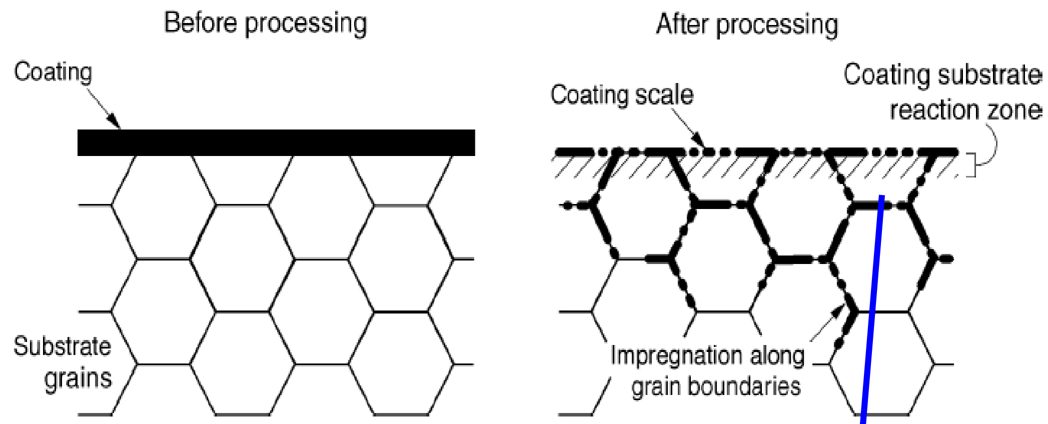
However, this approach tends to be more expensive and may not be acceptable for aesthetic reasons.

Laser Surface Heat Treatment

3. Key Process Parameters

Surface Coating

1. High-thermal stability.
2. Good adhesion to work surface.
3. Chemically passive to workpiece (metal oxide).
4. Easy to remove after treatment.



1. A dispersion of carbon black in alcohol with a binder (colloidal graphite).
2. Chemically deposited copper selenide layer (about 2 m thick).
3. Manganese, zinc, or iron phosphate (about 2–100 m thick).
4. Black paint (about 10–20 m thick).

- ✓ form low-melting compounds where failure can be initiated.
- ✓ an environmental hazard (especially paints) when they are vaporized during heating

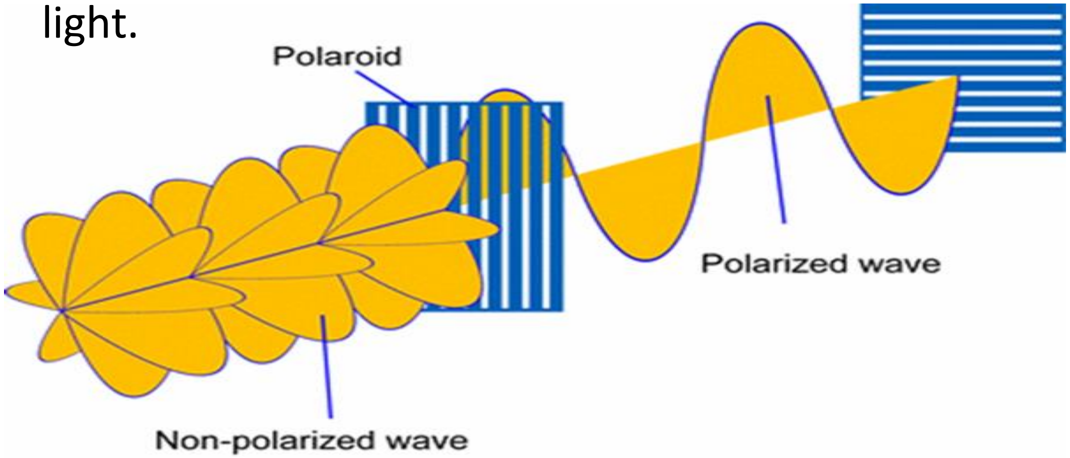
- ✓ After coating, 60–80% for a CO2 laser .
  - ✓ Graphite is easily applied and is inert, but is relatively more expensive.

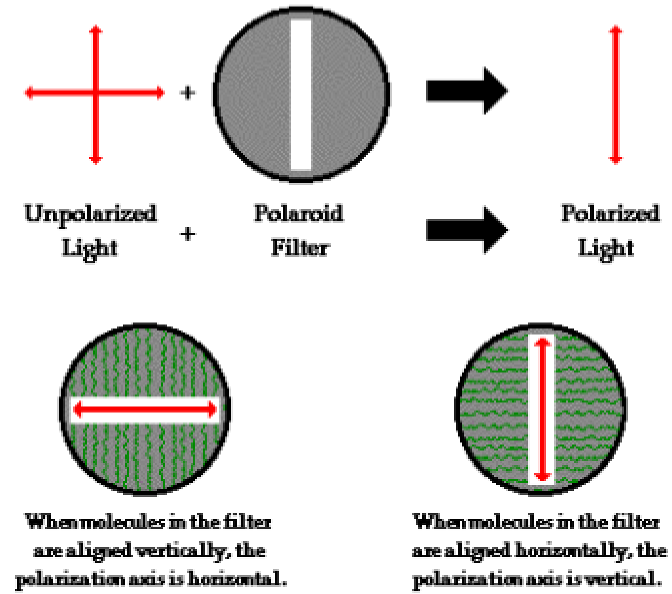
Laser Surface Heat Treatment

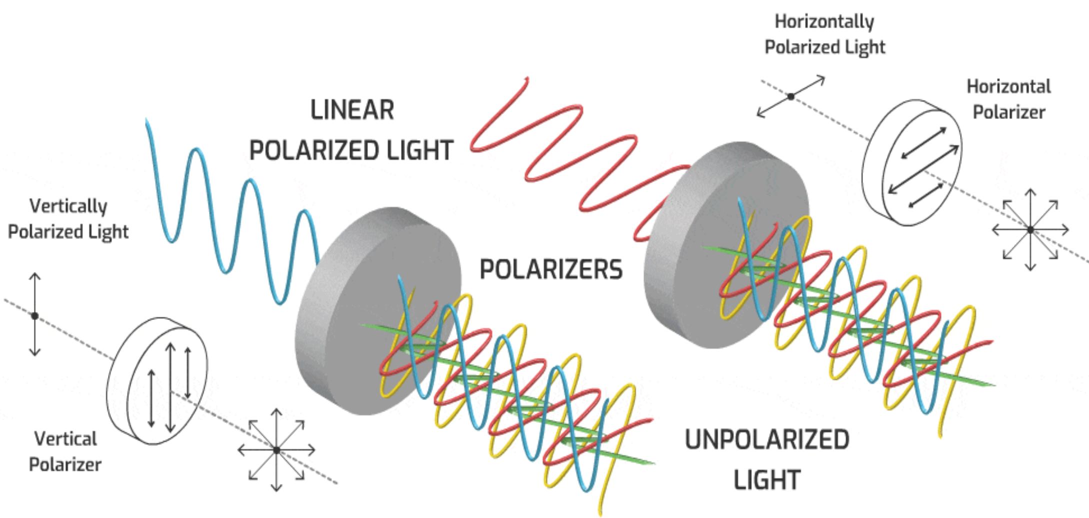
3. Key Process Parameters

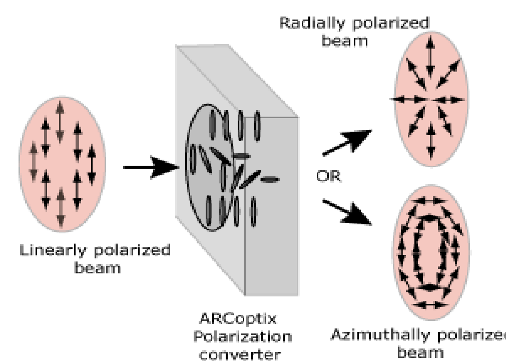
Polarized Beam

Polarization is the property of wave that can oscillate with more than one orientation or plane. A light wave that is vibrating in more than one plane is referred to as unpolarised light.









Laser Surface Heat Treatment

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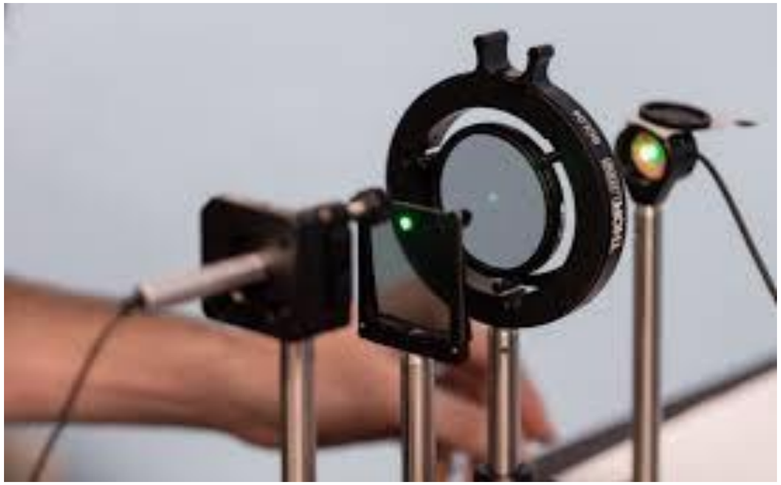
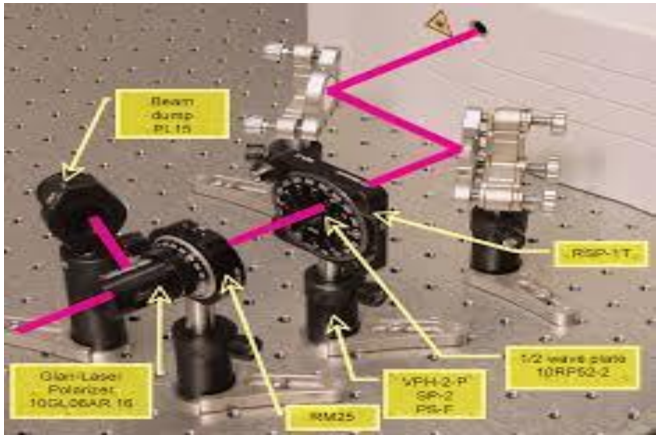
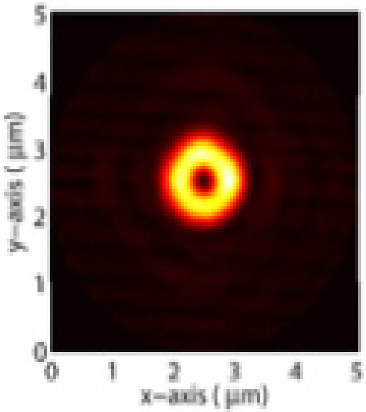
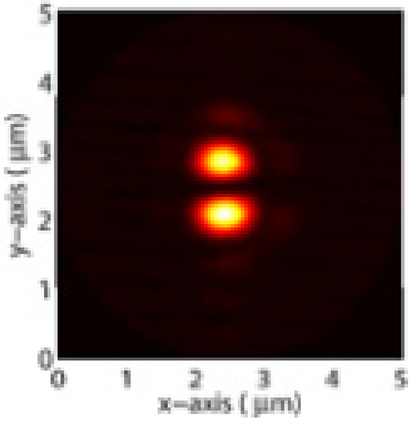






TEM 01*



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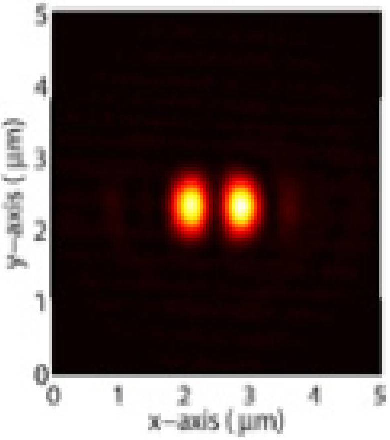

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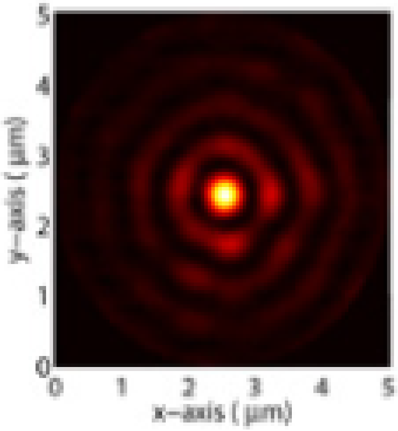
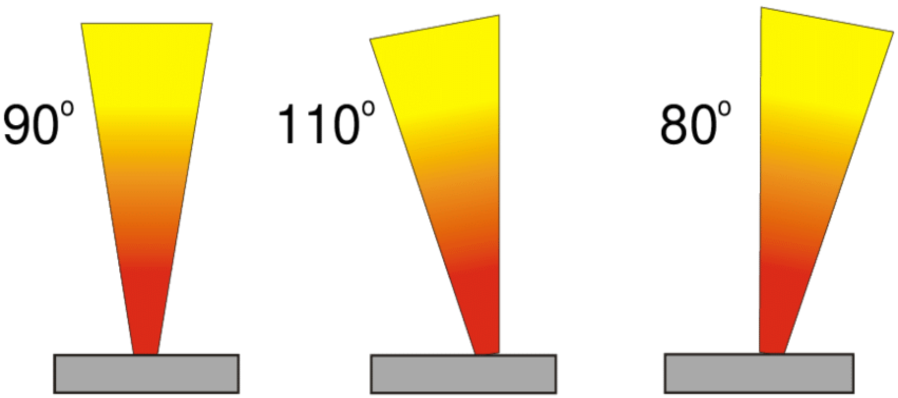


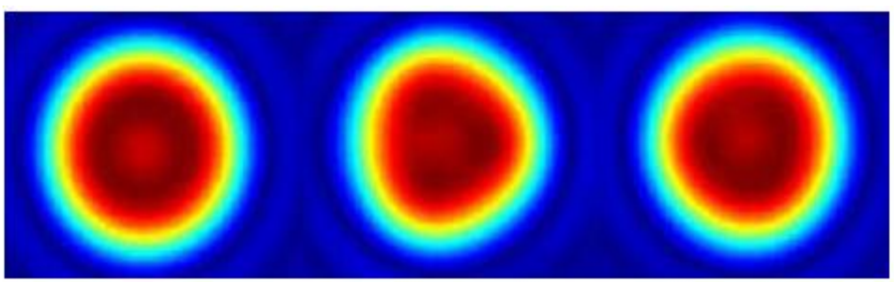
TEM30

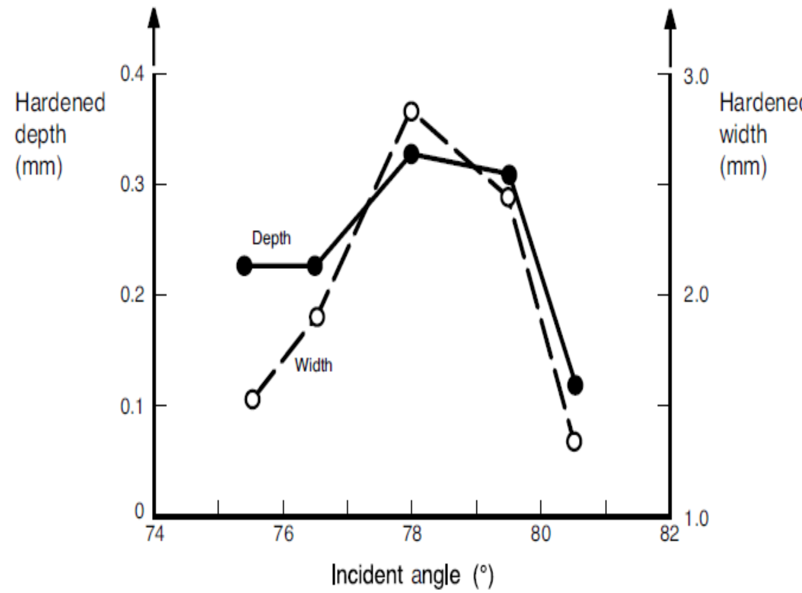
Laser Surface Heat Treatment

3. Key Process Parameters

Angle of incidence







Different shapes for different angle on the surface

Laser Surface Heat Treatment

3. Key Process Parameters

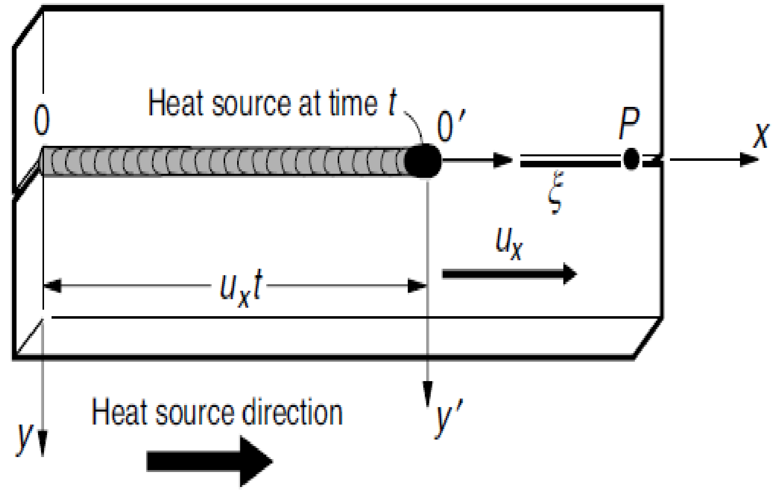
Preheating

- The absorptivity of a material increases with an increase in its temperature, for a given wavelength.
- Thus, one effective way for enhancing absorption of the incident laser is to preheat the workpiece before the heat treatment process.
- The drawback with this approach, however, is that preheating introduces an additional step into the process.
- Furthermore, the preheating may affect the microstructure of the surrounding material.

Laser Surface Heat Treatment

4. Temperature field

Analysis of heat flow during laser surface treatment



Since absorption of the laser beam in a solid metal is confined to a thin surface layer, the z-dependence of the absorption can be neglected.

Absorption considered to be two dimensional.

Considering a Gaussian distributed heat source moving in a semi-infinite plate in the x-direction, the temperature distribution in the y–z plane can be expressed as

$$T - T_0 = \frac{(1-R)q}{2\pi u_x k[t(t+t_0)]^{1/2}} \times \exp\left\{-\left[\frac{(z+z_0)^2}{4\kappa t} + \frac{y^2}{4\kappa(t+t_0)}\right]\right\}$$

$z = z_0$

where t is the interaction time, $t_0 = w^2/4k$ is the time required for heat to diffuse a distance equal to the beam radius, and z_0 is the distance over which heat can diffuse during the beam interaction time, w/ux.

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Laser Surface Heat Treatment

5. Microstructural Changes in Steels

- Steels are extensively discussed in this section because they are still among the most widely used metal alloys today.
- Some metals undergo polymorphic transformation (i.e., change their crystal structure) when heated above a certain temperature.
- An example is iron which changes from α-iron with the BCC structure at room temperature to γ-iron with the FCC structure when heated above 910◦C.
- The solubility of carbon in γ-iron is greater than in α-iron, and this makes steel subject to significant changes in property when heat treated.

The overall transformation process during heat treatment of steels occurs in three stages:

1. pearlite to austenite

2. homogenization of carbon in austenite

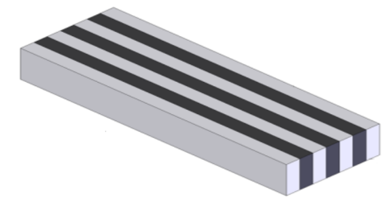
3. austenite to martensite

Laser Surface Heat Treatment

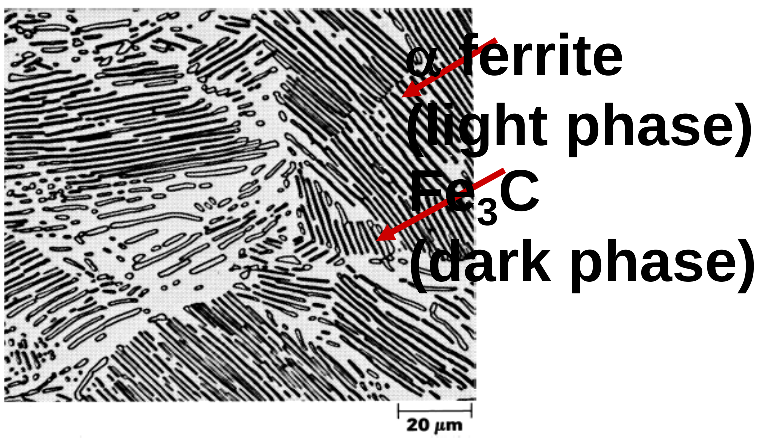
5. Microstructural Changes in Steels

1. pearlite to austenite

- Pearlite is a mixture of ferrite and cementite and it is an iron alloy that contains around 88% ferrite and 12% cementite.
- The mixture is in lamellar form, i.e., it is composed of alternate layers of ferrite and cementite.

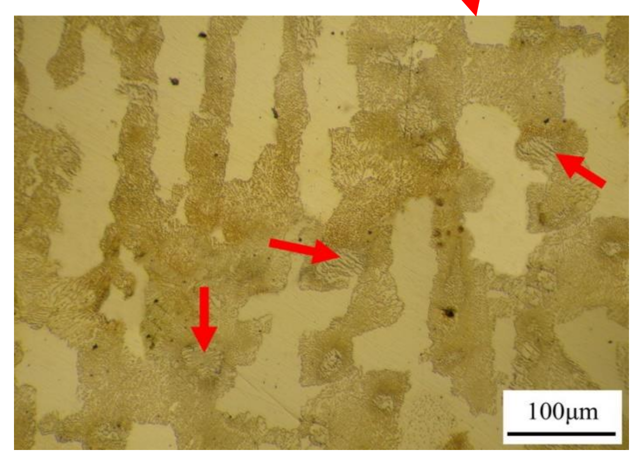


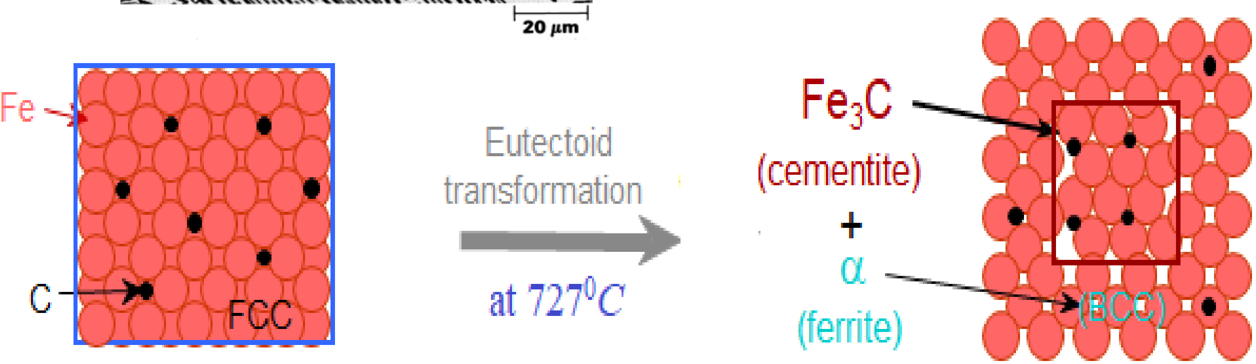
lamellar form



Pearlite has mechanical properties between the soft, ductile ferrite and the hard, brittle cementite.

Formation of pearlite





Laser Surface Heat Treatment

5. Microstructural Changes in Steels

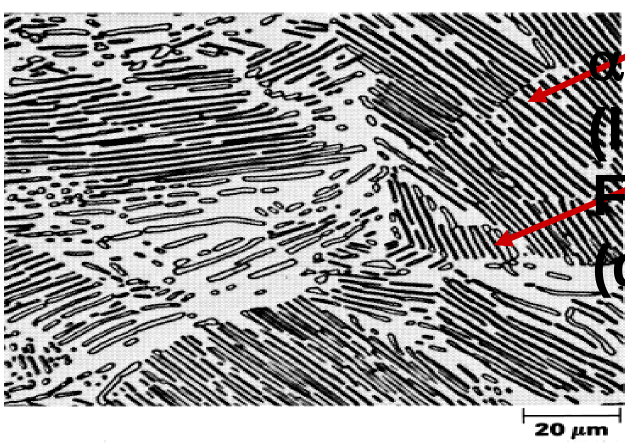
1. pearlite to austenite

In general, two processes accompany the phase transformation such as the eutectoid reaction (at 727^{0}C).

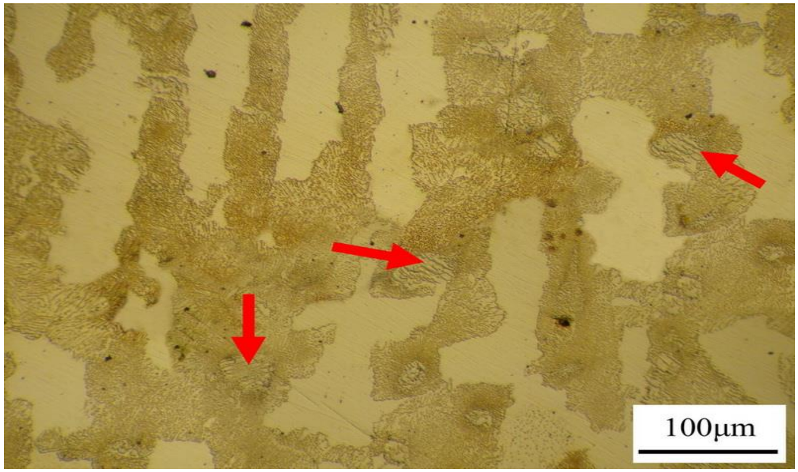
- **Nucleation — the formation of very small particles, or nuclei, of the new phase.**
- **Growth — the increase of the nuclei in size. Some volume of the parent phase disappears.**

Above eutectoid temperature: only austenite exists

Below eutectoid temperature: nucleation + growth



α ferrite (light phase)
Fe_3C (dark phase)



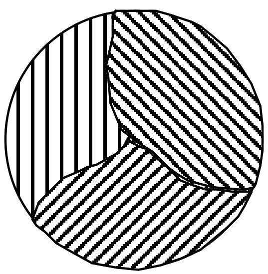
Laser Surface Heat Treatment

<u>5. Microstructural Changes in Steels</u>

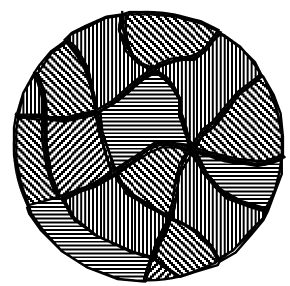
1. pearlite to austenite

The thickness of the ferrite/cementite layers in pearlite depends on the temperature. With decreasing temperature, the layers become progressively thinner.

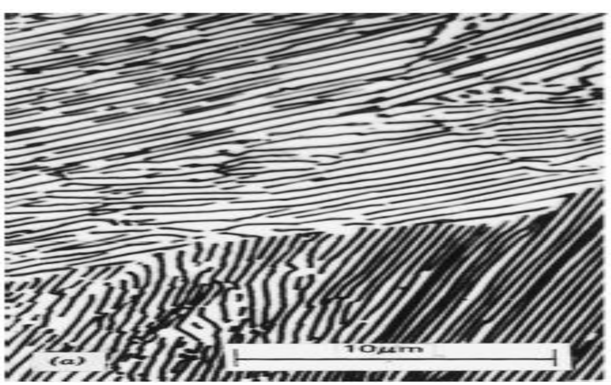
- **At temperatures <u>just below</u> eutectoid → relatively <u>thick</u> layers → <u>coarse</u> pearlite**
- **In the vicinity of <u>727</u>°C → <u>relatively thin</u> layers → <u>fine</u> pearlite**



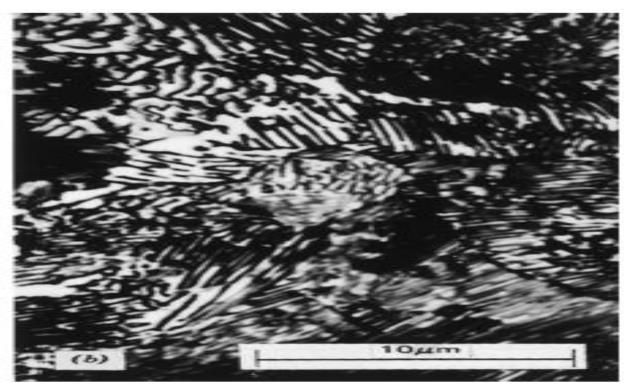
- Smaller ΔT: colonies are larger



- Larger ΔT: colonies are smaller



(a) Coarse Pearlite



(b) Fine Pearlite

Laser Surface Heat Treatment

5. Microstructural Changes in Steels

2. Homogenization of carbon in austenite

- Carbon diffuses from the high to the low concentration regions, which depends on temperature and time.

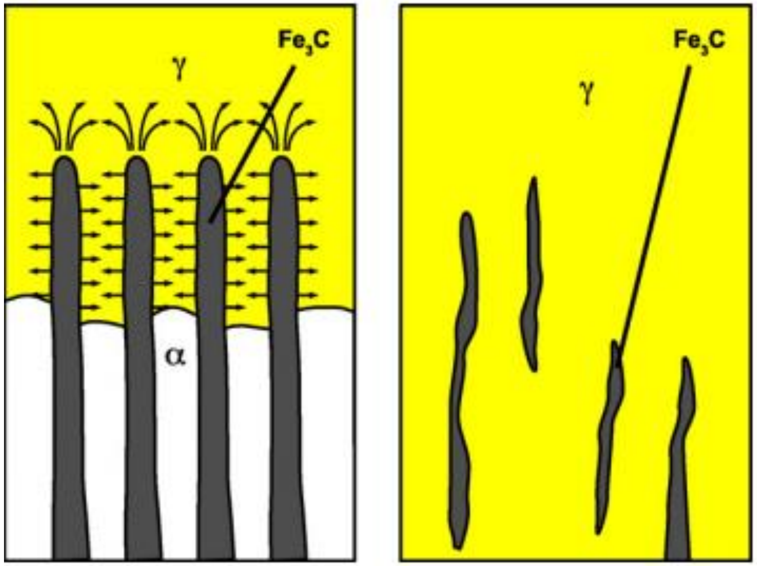
- Carbon required sufficient time for lateral diffusion. This time is given by

$$\lambda^2 = 2Dt$$ λ is the pearlite spacing within a colony.

The boundary region where carbon % increased is given by,

$$x = \frac{2}{\sqrt{\pi}} \ln \left(\frac{Ce}{2Cc}\right) \sqrt{Dt}$$

D is the diffusion coefficient for carbon, Ce = 0.8% is the pearlite carbon content, Cc = Critical carbon content C % (0.05%) is converted to martensite



Laser Surface Heat Treatment

5. Microstructural Changes in Steels

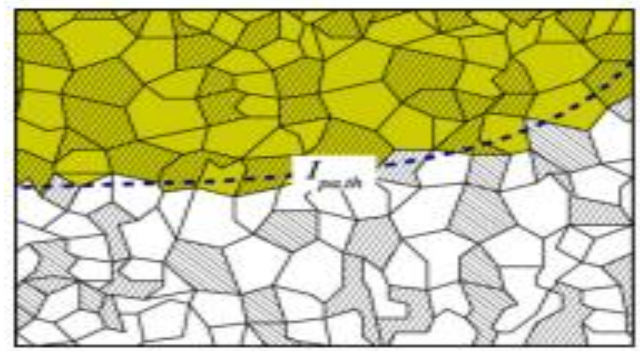
3. Austenite to martensite

- Martensite is normally formed when austenite is cooled. It is extremely hard and brittle. The transformation from austenite to martensite is diffusionless.
- Volume fraction of martensite depends on grain size and volume fraction of pearlite colonies.

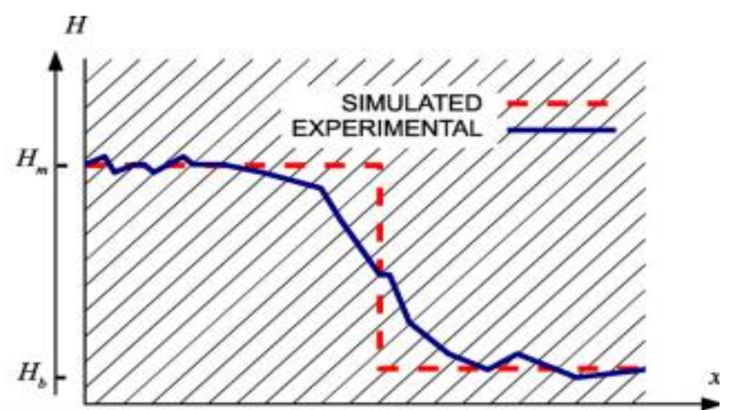
The volume fraction f of martensite that is formed over a period t is given by

$$f = f_{\mathrm{m}} - (f_{\mathrm{m}} - f_{\mathrm{i}}) \exp\left[-\frac{12 f_{\mathrm{i}}^{2/3}}{g_{\mathrm{s}}\sqrt{\pi}} \ln\left(\frac{C_{\mathrm{e}}}{2C_{\mathrm{c}}}\right)\sqrt{D_{\mathrm{a}} t}\right]$$

$$f_{\mathrm{m}} = \begin{cases} 0 & \text{if} \quad T_{\mathrm{p}} < A_1 \\ f_{\mathrm{i}} + (1 - f_{\mathrm{i}})\frac{T_{\mathrm{p}} - A_1}{A_3 - A_1} & \text{if} \quad A_1 < T_{\mathrm{p}} < A_3 \\ 1 & \text{if} \quad T_{\mathrm{p}} > A_3 \end{cases}$$



A1 is the eutectoid temperature, A3 = 1183 − 416Ca + 228Ca^2 K is the lower temperature boundary of the austenite zone



Where fi = volume fraction of pearlite = C/0.8 , is the volume fraction initially occupied by the pearlite colonies, which is also the minimum subsequent volume fraction of martensite. gs is the average austenite grain size, fm is the maximum volume fraction.

Laser Surface Heat Treatment

6. Non ferrous alloy

- Other materials can also be subjected to laser heat treatment to improve their mechanical properties.
- The hardness of some aluminum alloys, for example, can be increased by about 100% after laser treatment.
- The strength of nonferrous alloys can be increased by precipitation hardening.

1. Solution treatment.
2. Quenching
3. Aging.

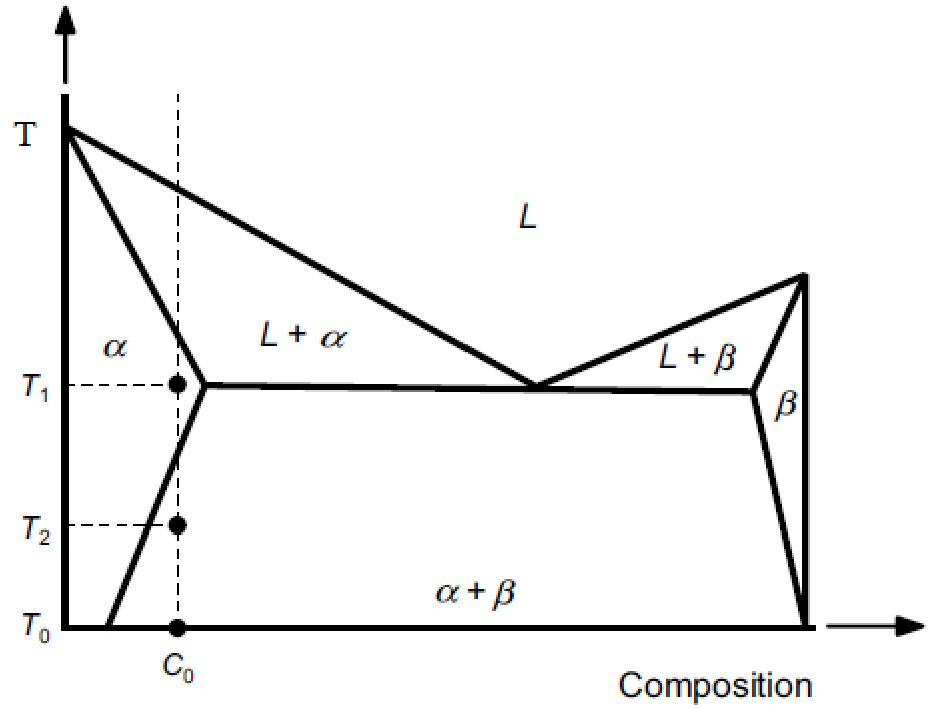
Solution treatment

- The material is heated into the portion of the phase diagram where only a solid solution phase exists, say T1 and allowed to stay until the solid solution phase, α, is formed.
- The metal is treated with a solution at high temperatures, slightly below the **eutectic point** of the material. Too low and the solution annealing is ineffective; too high and metals reach their melting point.
- In this process, inhomogeneities are transformed into homogeneities.

Laser Surface Heat Treatment

6. Non ferrous alloy

1. Solution treatment.
2. Quenching
3. Aging.



Quenching

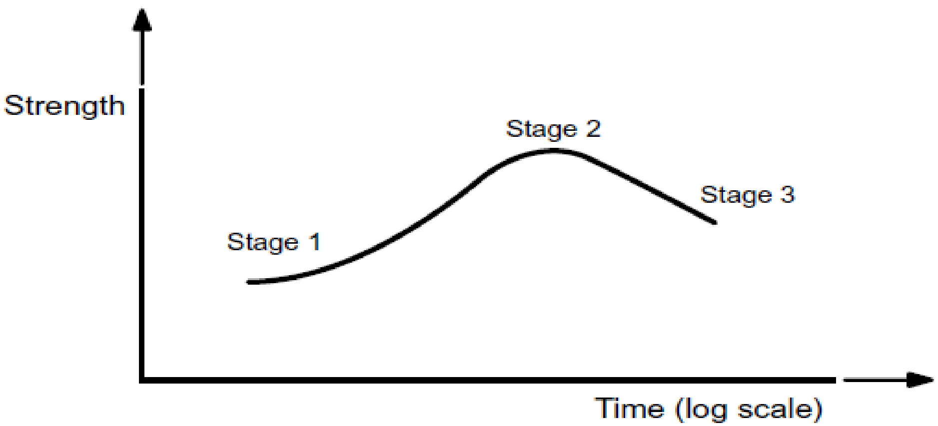
- It is then quenched to T2. The rapid cooling prevents the formation of the second phase, β, and the alloy formed at this stage is supersaturated, and initially relatively soft.

Aging

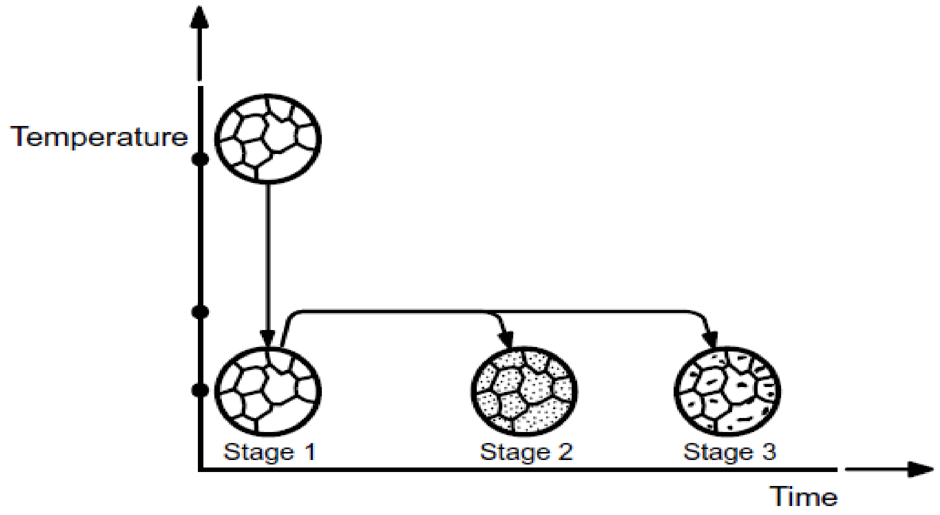
- If the alloy is maintained at T2 for a while, nuclei of the second phase are formed and begin to grow throughout the material, resulting in second phase particles.
- The formation of the second-phase particles impede the motion of dislocations. That means more stress is required to move the dislocations through them, and the strength of the material thus increases.
- The more particles are formed and grow, the greater the strength becomes (stage 1). Thus a finer distribution of second phase particles produces a stronger material.

Laser Surface Heat Treatment

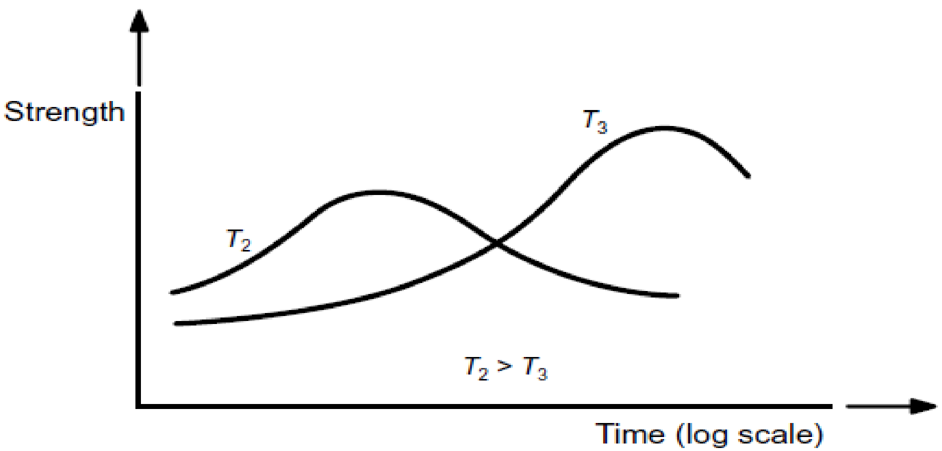
6. Non ferrous alloy



(a)



(c)



(b)

(a) Variation of hardness with time during aging

(b) Temperature dependence of the aging curve

(c)Variation of microstructure with time during aging

Laser Surface Heat Treatment

6. Non ferrous alloy

Aging

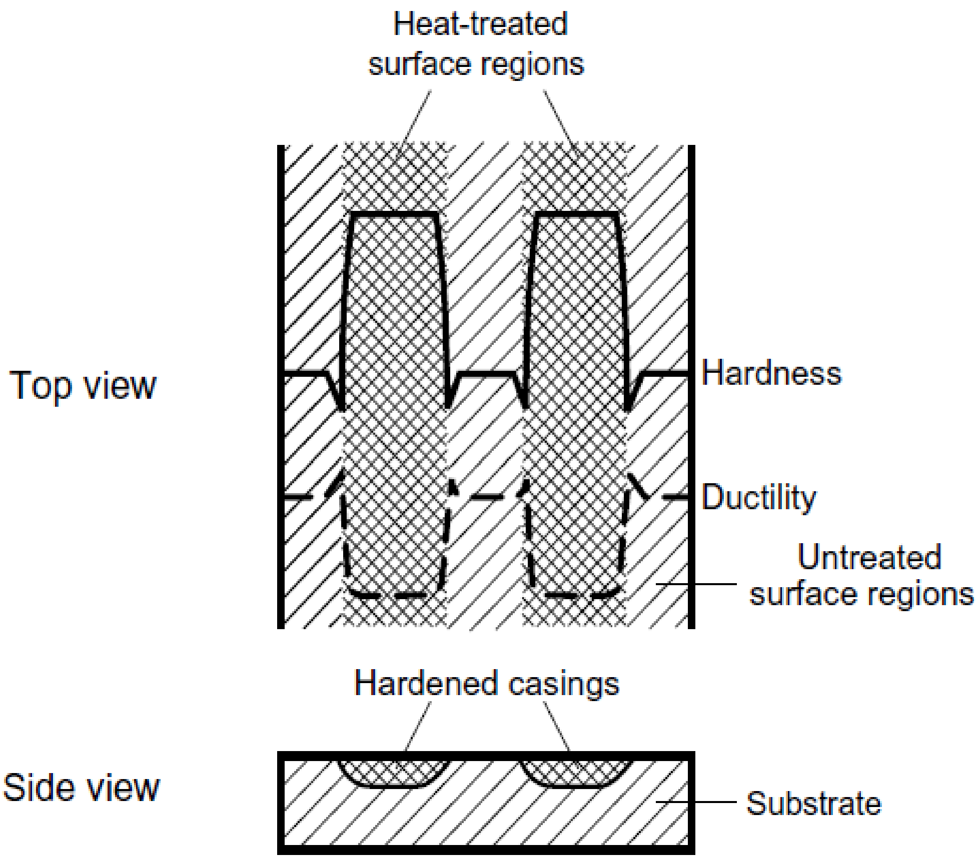
- However, eventually the strength reaches a maximum (stage 2) and a further stay at T2 only results in continued growth of the particles as smaller particles join together to form larger ones, and the spacing between them increases. The strength then begins to decrease (stage 3). This is overaging.
- The lower the aging temperature, T3, the longer it takes to reach the maximum strength, but the greater is the maximum strength since the second phase is more finely dispersed at the lower temperatures due to the increased nucleation rate.
- If T3 is low enough, the second phase may not form at all.

Nonferrous alloys may also be hardened by laser treatment if at least one of the following conditions is satisfied:

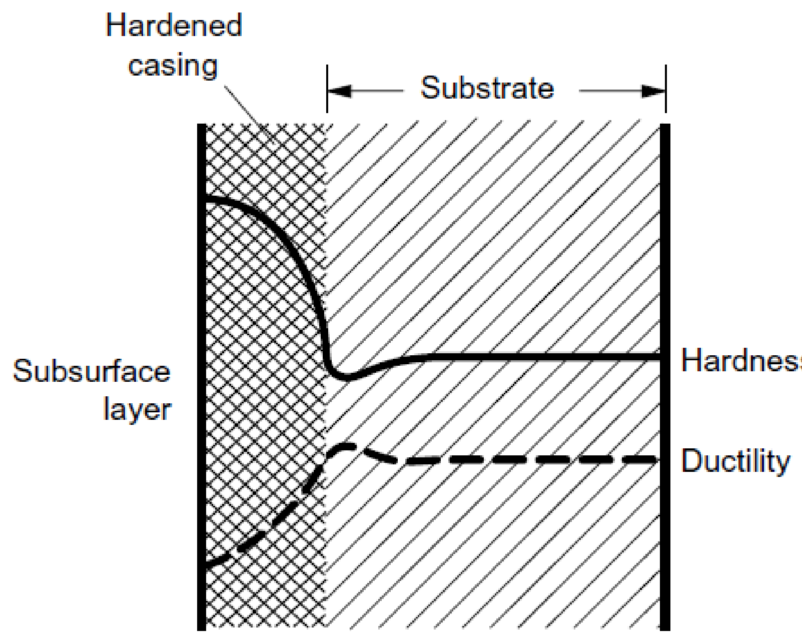
1. Formation of a characteristic finely divided structure in the hardening zone.
2. Formation of metastable phases.
3. Dislocation density increase.

Laser Surface Heat Treatment

7. Hardness Variation



(a)



(b)

(a) Hardness distribution on the top surface of the workpiece

(b) Hardness variation with depth

Laser Surface Heat Treatment

8. Residual Stresses

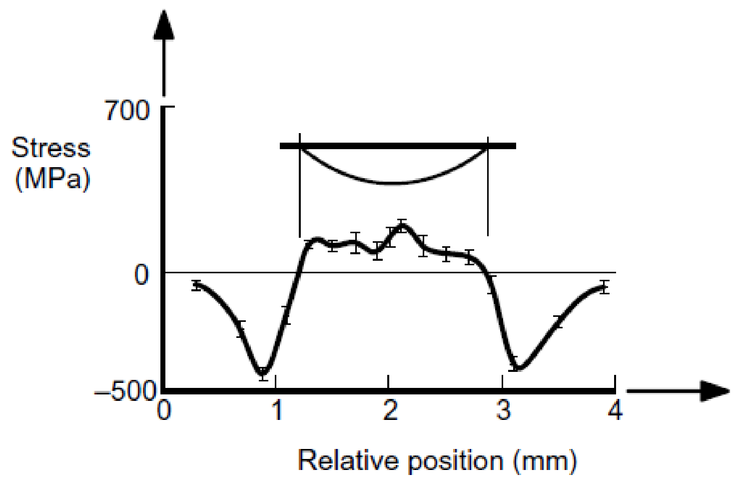
Residual stresses are normally induced in the surface layers of a part that is subjected to surface modification.

The key mechanisms responsible for the residual stresses are the following:

1. Thermal expansion and contraction associated with the process
2. Phase transformation, as occurs during austenite to martensite transformation.

❑ The second mechanism is due to an increase in volume as austenite transforms to martensite, resulting in compressive stresses. These compressive residual stresses improve the fatigue life of the part.

❑ The variation of transverse stresses across the laser track for a single scan laser heat treatment is shown in Fig. 17.16a, indicating tensile transverse stresses within the laser track, with balancing compressive stresses in the heat-affected zone outside the track.



Laser Surface Heat Treatment

9. Advantages of LSHT

1. Rapid heating and cooling. This enables steels of lower hardenability to be heat treated. Thus it is often suitable for components that are difficult to harden using conventional methods such as flame and induction hardening.
2. The resulting heat-affected zone is minimal, compared to that associated with flame and induction hardening.
3. Minimal distortion due to low-heat input. This eliminates posthardening machining.
4. Localized heat input enables only desirable regions to be heat treated. Other regions are thus essentially unaffected. It also minimizes the total heat input to the part. Thus less energy is used.
5. Ease of processing complex shapes due to the ability to scan the beam over the part.

Laser Surface Heat Treatment

9. Advantages of LSHT

6. More uniform case hardness.
7. No external quenching is necessary since the process often involves self-quenching.
8. Minimization of fumes and dirt that result from heating and quenching.
9. The short cycle time results in relatively fine-grained structure. This enables higher strength and good fatigue resistance to be achieved.

10. Disadvantages of LSHT

1. Due to the short interaction times, coarse structures (or alloys that require long soaking times for heat treatment) tend to be difficult to laser heat treat. These include coarse pearlite, blocky ferrite, and steels that contain spheroidal carbides and cast irons that consist primarily of graphite without any pearlite. The austenite may not be completely homogenized in such materials, and thus soft spots may occur in the hardened zone.
2. High-capital cost of the laser.
3. The need for sufficient mass for self-quenching.