Laser Hardening of Steel

• Steel (Iron/Carbon combination)
• Many different crystal phases with different hardness/ductility tradeoffs
• At 800°C 4% carbon steel changes to Austenite form
• Causes carbon to redistribute
• If quenched < 1 sec get Martensite very hard but brittle layer
• Called Case Hardening
• Can be applied by laser to just local areas

Fig. 4.6. Metallurgical description of laser heat treatment.
Laser Parameters and Case Hardening

- Can tradeoff laser power and time
- Recall from uniform heating the surface temperature

$$\Delta T(0,t) = \frac{2H}{k} \sqrt{\frac{\alpha t}{\pi}}$$

- Thus for the same material $T$ is proportional to $H \sqrt{t}$
- Thus doubling power cuts time by 4
- However depth of heat zone is changed because

$$\frac{T_m}{T_v} = \sqrt{\frac{\pi}{2}} \text{erf} c \left( \frac{z}{2\sqrt{\alpha t}} \right)$$

![Laser Parameters and Case Hardening](image.png)

**Fig. 5.8** Curves showing the maximum temperatures reached as a function of depth in 1045 steel. Curve $C_1$ corresponds to a heat input of $2.5 \times 10^7$ W m$^{-2}$ applied for 0.4 s, while $C_2$ corresponds to $5 \times 10^7$ W m$^{-2}$ applied for 0.1 s. The intersection of these curves with the horizontal lines corresponding to the temperatures $A_3$ and $A_1$ enables the appropriate case-hardening depths and transition zones to be determined.
Spreading the Laser Beam

- To evenly heat the surface
- Defocus the laser beam
- Transport surface (rasterized beam)
  - either zig zag or circular
- Mirrors spreading

Figure 13-2  Defocused laser beam incident on workpiece for heat treating.

Figure 13-3  Active methods for spreading out a laser beam for surface treatment applications.
Mirrors & Lenses to Expand the laser Beam

(a) Unfocussed beam

(b) Restored beam

(c) Kaleidoscope

(d) Beam integrator (segmented mirror)

(e) Axicon lens

(f) Toric mirror

(g) Kinoform (holographic mirror)
Modification of Surface Reflectivity

- Reducing reflectivity important for lower power
- Roughen surface: increases scatter
- Oxidize surface (very good for iron)
- Coat surface
- Most useful for Annealing, not useful if melting occurs
  melt destroys these processes

<table>
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<tr>
<th>Table 6.1</th>
<th>Typical values of the reflectivity of various surfaces to 10.6μm radiation at normal angles of incidence.</th>
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<td>Surface Type</td>
<td>Reflectivity %</td>
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<td>Sandpaper roughened (1μm)</td>
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<td>Sandblasted (19μm)</td>
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<td>Sandblasted (50μm)</td>
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<td>Oxidised</td>
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<td>Graphite</td>
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<td>Molybdenum sulphide</td>
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<td>Dispersion paint</td>
<td>0.9</td>
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</tbody>
</table>
Laser Recrystallization of Poly Silicon

- Poly Silicon is common conductor in IC's
- Grain size very sensitive to production temperature
- But want low temperatures to reduce effects on substrate
- Poly Si's electrical parameters much poorer than single crystal Si
- Thus attempts at laser recrystallization to get near single crystal behavior
- Some attempts to build stacked transistors one transistor above another recrystallized poly Si used as the 2nd layer

Fig. 15 Average crystallite size $S$ for phosphorus-doped LPCVD silicon layers as-grown ($o =$ interface, $\Delta =$ surface), and annealed at 1000$^\circ$C ($\circ =$ interface, $\nabla =$ surface) as a function of
Laser Recrystallization of Poly Silicon

- Successfully recrystallized silicon
- However do not need laser to do this:
  - Used just regular light sources
  - Called Rapid Thermal Anneal

Fig. 7.16. Growth of large grain polysilicon from small grain CVD poly by scanning CW laser beam.
Laser Surface Melting

- Want to melt the surface locally
- Melt & rapid solidification
  - get fine homogeneous structures (recrystallize)
- Little thermal penetration
  - thus small thermal distortion for sensitive materials
- Melt gives surface finishes within 25 microns
  - reducing finishing work
- Process flexibility: easy to software control

Fig. 6.23. forces on the melt pool.
Case Iron Laser Surface Melting

- Melting causes carbon redistribution
- Forms Martensite & Cementite phases significantly increase hardness of Cast Iron

Fig. 6.26. Theoretical calculation of the position of the melt front during preplaced powder cladding (51).

Figure 13-5  Micrographs of heat treat tracks. (Courtesy of Saginaw Steering Gear, Division of GMC.)
Titanium

- Laser heating creates very fine crystal structure
- Must be done in inert atmosphere

Fig. 6.19. Micrograph showing the fine basket weave structure produced in laser surface melting IMI550 (28) (P = 1.6 kW; V = 200 mm/s; D = 0.5 mm). X 100
Laser Surface Alloying

- Coat surface with film of another material
- Melt layer with laser locally
  (may inject material into melt pool also)
- Rapid quenching
- Alloyed layer has fine microstructure, nearly homogeneous
- Many materials alloyed into substrates
- Some materials only possible with rapid quench of laser
- Thickness form 1 to 2000 microns

Applications
- Cast Iron: Cr, Si, C makes expensive steel surface on cheap iron mass
- Steel: Cr, N, Mo, B
- Aluminium: Si, C, N, Ni alloying

![Diagram of laser alloying process]
**Laser Cladding**

- Overlay one material with another
- Usually powders or Chemical Vapours are sources
- Most common industrial is powder process
- Powder blown onto surface
- Laser melts power to surface cladding

![Image of laser cladding process]

*Fig. 6.2. A blown powder laser clad being formed.*
Laser Cladding

- Powder could be pre-placed
- Melt goes rapidly through powder
- Powder has little thermal contact with substrate
- When molten heat load increase due to good thermal contact
- Then melt into substrate and fuse with it

Fig. 6.26. Theoretical calculation of the position of the melt front during preplaced powder cladding (51).
Laser Cladding Setup

- Use reflective dome above powder
- Recovers powder
Laser Cladding

- Shows big improvement when surface roughness changes
- Power sensitive to cladding thickness

Fig. 6.28. The left side of the substrate was shot blasted. The right side had a ground finish. The upper track was made without the reflective dome; the lower track was made using the dome to recycle reflected energy (38).

![Graph](image-url)
Laser Welding

- Laser welding involves melting two surfaces together
- Generally two types
- Conduction weld: just melt but do not vaporize
- Keyhole weld, some vaporization and deep weld

Fig. 4.6. Conduction limited and “keyhole” type welds.

Figure 13-11  Micrograph of laser weld.
**Keyhole weld**

- May need to melt two or more layers
- Melt pole stabilized by vapor

<table>
<thead>
<tr>
<th>Table 4.3</th>
<th>Main Characteristics of Laser Welding</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Characteristic</strong></td>
<td><strong>Comment</strong></td>
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<tr>
<td>High energy density - &quot;keyhole&quot; type weld</td>
<td>Less distortion</td>
</tr>
<tr>
<td>High processing speed</td>
<td>Cost effective (if fully employed)</td>
</tr>
<tr>
<td>Rapid start/stop</td>
<td>Unlike arc processes</td>
</tr>
<tr>
<td>Welds at atmospheric pressure</td>
<td>Unlike EB welding</td>
</tr>
<tr>
<td>No X-rays generated</td>
<td>Unlike EB</td>
</tr>
<tr>
<td>No filler required (autogeneous weld)</td>
<td>No flux cleaning</td>
</tr>
<tr>
<td>Narrow weld</td>
<td>Less distortion</td>
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<tr>
<td>Relatively little Heat Affected Zone (HAZ)</td>
<td>Can weld near heat sensitive materials</td>
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<tr>
<td>Very accurate welding possible</td>
<td>Can weld thin to thick materials</td>
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<tr>
<td>Good weld bead profile</td>
<td>No clean up necessary</td>
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<tr>
<td>No beam wander in magnetic field</td>
<td>Unlike EB</td>
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<tr>
<td>Little or no contamination</td>
<td>Depends only on gas shrouding</td>
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<tr>
<td>Relatively little evaporation loss of volatile components</td>
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<tr>
<td>Difficult materials can sometimes be welded</td>
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<tr>
<td>Relatively easy to automate</td>
<td>General feature of laser processing</td>
</tr>
<tr>
<td>Lasers can be time shared</td>
<td>General feature of laser processing</td>
</tr>
</tbody>
</table>

---

**Fig. 4.2. Industrial applications of Nd-YAG lasers 1986.**

**Fig. 4.3. Industrial applications of CO₂ lasers 1986.**
### Table 4.1 Relative Power Densities of Different Welding Processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Heat Source Intensity $\frac{W}{m^2}$</th>
<th>Fusion zone profile</th>
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<tbody>
<tr>
<td>Flux Shielded Arc Welding</td>
<td>$5 \times 10^6 - 10^8$</td>
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<tr>
<td>Gas Shielded Arc Welding</td>
<td>$5 \times 10^6 - 10^8$</td>
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<tr>
<td>Plasma</td>
<td>$5 \times 10^6 - 10^10$</td>
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</tr>
<tr>
<td>Laser or Electron Beam</td>
<td>$10^10 - 10^{12}$</td>
<td></td>
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### Table 4.2 Relative Joining Efficiencies of Different Welding Processes

<table>
<thead>
<tr>
<th>Process</th>
<th>Approximate Joining Efficiency $mm^2/kJ$</th>
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<tbody>
<tr>
<td>Oxy Acetylene Flame</td>
<td>0.2 - 0.5</td>
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<tr>
<td>Manual Metal Arc (MMA)</td>
<td>2 - 3</td>
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<tr>
<td>Tungsten Inert Gas (TIG)</td>
<td>0.8 - 2</td>
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<tr>
<td>Submerged Arc Welding (SAW)</td>
<td>4 - 10</td>
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<tr>
<td>High Frequency Resistance Welding</td>
<td>65 - 100</td>
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<tr>
<td>Electron Beam (EB)</td>
<td>20 - 30</td>
</tr>
<tr>
<td>Laser</td>
<td>15 - 25</td>
</tr>
</tbody>
</table>
Keyhole Welding of Lasers

- May need to melt two or more layers
- Use keyhole melt pool stabilized by vapour

Fig. 4.7. Approximate shape and flow pattern in laser welds.
Plasma Absorption

- If get too much vapor can form plasma
- Laser ionizes vapor
- Plasma heavily adsorbs beam
- Get a pulse effect as plasma comes off

Fig. 4.9. Illustration of the blocking effect of the plasma if there is no side jet removing it.
Gas shielding

- Use inert gas flow to shield weld
- also reduces plasma effect if high flow

Fig. 5.11 Schematic beam focusing head design for laser welding when using a shielding gas.
Laser Welding Setup

- Many laser parameters affect welding
- Affected also by type of weld
- Gap between materials important

Laser Beam: Spot Size
- Focal Position
- Energy/Power
- Pulsed/CW
- Pulse Shape
- Pulse Rate
- Beam Mode
- Polarisation

Shielding Gas:
- Composition
- Shroud Design
- Velocity

Surface Conditions

Joint/Weld Geometries
- Square Weld
- Spot/Spike Weld

Gap Tolerance
- Metal Thickness
- Metal Compositions

Weld Speed
- % Overlap
Types of Laser Welds

- All the classic weld joints

(a) Butt Joint
(b) Fillet or Lap Joint
(c) Spot or Lap Weld
(d) Spike or Spot Weld
(e) Flange Joint
(f) Edge Joint
(g) T-Joint
(h) Flare Weld
(i) Corner
(j) Kissing or flare Weld
Microelectronic Applications

- Use laser to make microwelds on circuits
- Used for bonding wires rather than ball bonder
- Widely used in production:
  - make many welds at once
- 20% stronger and can be done closer together

Fig. 5.14 A comparison between (a) a conventionally made microweld and (b) one made with a laser (CO₂). The connecting wires in fact link chips in a microcomputer. According to Amdahl the laser-made welds are cleaner, some 20% stronger and, because of increased precision, enable the components to be some 90% closer together (Courtesy Amdahl Corporation).
Laser Cutting Advantage

- Accounts for 82% of CO$_2$ laser work
  43% of Nd:Yag (1986)
- Cut width (Kerf) very narrow
- Edges square, not rounded
- Cut edge very smooth, can be welded directly
- Little edge burr compared to others methods
- Heat Affected Zone (HAZ) thin, hence little distortion
- Cutting done in hidden areas
- Cut depth is limited (1-2 cm) and controllable
- Very fast cut, no clamping needed
- No noise
- Wide range of materials (including brittle & fragile)
# Laser Cutting Advantages

## Table 3.1. Comparison of Different Cutting Processes

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<tr>
<th>QUALITY</th>
<th>Laser</th>
<th>Punch</th>
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<th>Abrasive Fluid Jet</th>
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</tbody>
</table>

✔ Point of particular merit
× Point of particular disadvantage

(Further comparisons can be found in ref 1)
Laser Cutting

- Recall the 6 basic ways

**Vaporization**
- Beam heats local area above melting point
- Material boils and ejects

**Melting and Blowing**
- Beam melts surface, jet of inert gas removes material

**Burning in Reactive Gas**
- Beam melts surface, jet of reactive gas removes material
- Gas (usually oxygen) reacts with material, adds energy

**Thermal stress Cracking**
- Heat/cool cycle creates thermal stress, material breaks
- Requires least energy

**Scribing**
- Cut creates small stress point, breaks with force

**Cold Cutting**
- Laser photons cause material to disassociate

<table>
<thead>
<tr>
<th>Table 3.2.</th>
<th>Different ways in which the laser can be used to cut.</th>
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<td>3. Melt, burn and blow</td>
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<td>4. Thermal stress cracking</td>
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<td>5. Scribing</td>
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