Temperature Change for Uniform Illumination

- Assume that the surface is uniformly illuminated by the laser
- Energy absorbed at the surface in a very small depth

\[ H = I(1-R) \]

where \( R \) = reflectivity
\( I \) = light intensity

- The heat DE has been solved for depth \( z \) and time \( t \)
  (by Carslaw & Jaeger, 1959)

\[ \Delta T(z,t) = \frac{2H}{k} \sqrt{\alpha t} \text{ ierfc} \left[ \frac{z}{2\sqrt{\alpha t}} \right] \]

- The ierfc is the integral of the complementary error function

![Figure 12-1](image)

*Figure 12-1*  Ratio of temperature \( T \) at depth \( z \) to the surface temperature \( T_s \), versus \( z/\sqrt{4\kappa t} \) for uniform, constant irradiance.
Error Function Related Equations

- Heat flow equations are related to the Error Function erf

\[ \text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-s^2} ds \]

- This is the integral of a Gaussian between 0 and x
- The Complementary Error Function erfc

\[ \text{erfc}(x) = 1 - \text{erf}(x) \]

- erfc is the integral from x to infinity
- The ierfc is related to the error function by

\[ \text{ierfc}(x) = \int_x^\infty \text{erfc}(s) ds = \frac{1}{\sqrt{\pi}} \exp(-x^2) - x[1 - \text{erf}(x)] \]

- ierfc(1) = 0.05 and is falling rapidly

Fig. 5.3 Graph of the function ierfc(x)
Useful Error Function Approximations

• Error function erf(x), Complementary Error Function erfc(x) are

\[
\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-s^2} \, ds
\]

\[
\text{erfc}(x) = 1 - \text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-s^2} \, ds
\]

• erf(x) hard to find but easy to approximate with

\[
\text{erf}(x) = 1 - \left( a_1 t + a_2 t^2 + a_3 t^3 \right) e^{-x^2}
\]

\[
t = \frac{1}{1 + px}
\]

where \( p = 0.47047 \)

\( a_1 = 0.3480242, a_2 = -0.0958798, a_3 = 0.7478556 \)

• See Abramowitz & Segun (Handbook of Mathematical Functions)

• Error on this is \(< 2.5 \times 10^{-5}\) for all x

• We are using complementary error function

\[
\text{erfc}(x) = 1 - \text{erf}(x) \quad \text{erfc}(0) = 1 \quad \text{erfc}(\infty) = 0
\]

• Approximation has \(<2\%\) error for \( x << 5.5 \)

• For \( x > 5.5 \) use asymptotic approximation

\[
\text{erfc}(x) \rightarrow \frac{e^{-x^2}}{x \sqrt{\pi}} \left[ 1 - \frac{1}{2x^2} \right] \quad \text{as} \quad x \rightarrow \infty
\]

• Excel & Quatropro spreadsheet have erf() and erfc() built in. Must activate analysis toolpack & solver first but become inaccurate for \( x>5.4\) – then use asymptotic

• For \( x > 5.4 \) then ierfc(x) becomes

\[
\text{ierfc}(x) \rightarrow \frac{e^{-x^2}}{2x^2 \sqrt{\pi}} \quad \text{as} \quad x \rightarrow \infty
\]
**Temperature Rise for Uniform Illumination**

- From DE solution since ierfc is small for $x>1$
- Thus find that $T$ rise is small when

$$\frac{z}{2\sqrt{\alpha t}} > 1$$

- Hence small rise when

$$z^2 > 4\alpha t$$

- Heat will diffuse a depth $L$ in time of order

$$t = \frac{L^2}{4\alpha}$$

- Change in surface temperature with time
  substitute $z = 0$ and note

$$\text{ierfc}(0) = \frac{1}{\sqrt{\pi}}$$

- Thus surface temperature change is:

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

- Thus temp increases with $\sqrt{\alpha t}$

![Graph showing temperature rise over time for different depths](image)
Temperature Change with Finite Time Laser Pulse

- If have a square pulse of duration \( t_p \)
- The for \( t < t_p \) follow the previous formula
- For Time greater than the pulse

\[
\Delta T(z, t)_{t > t_p} = \delta T(z, t) - \delta T(z, t - t_p)
\]

- eg. Consider Cooper with \( H = 10^{10} \text{ W/m}^2 \) for \( t_p = 10^{-6} \text{ sec} \)
- From table \( \alpha = 1.16 \times 10^{-4} \text{ m}^2/\text{s} \)
- \( T \) rises highest at surface \((z=0)\) and changes fastest
- At pulse end heat has diffused about \( L \)

\[
L \approx \sqrt{4 \alpha t} \approx \sqrt{4(1.16 \times 10^{-4})(10^{-6})} = 2.15 \times 10^{-5} \text{ m}
\]

- At depth peak \( T \) occurs much later, and lower values

![Graph](image.png)

**Fig. 5.4** Calculated temperature increases at various depths \((z)\) below the surface of a semi-infinite copper block when irradiated with a constant heat pulse of \(10^{10} \text{ Wm}^{-2}\) for a time of 1 \( \mu\text{s}\).
Laser Focused into a Spot

- If laser focused into uniform spot radius \( a \) then formula changes to (by Carslaw & Jaeger, 1959)

\[
\Delta T(z,t) = \frac{2H}{k} \sqrt{\alpha t} \left\{ \text{erfc} \left( \frac{z}{2\sqrt{\alpha t}} \right) - \text{erfc} \left( \frac{\sqrt{z^2 + a^2}}{2\sqrt{\alpha t}} \right) \right\}
\]

- Term on right caused by sideways diffusion
- At the centre of the spot \( (z = 0) \)

\[
\Delta T(z,t) = \frac{2H}{k} \sqrt{\alpha t} \left\{ \frac{1}{\sqrt{\pi}} - \text{erfc} \left( \frac{a}{2\sqrt{\alpha t}} \right) \right\}
\]

- This gives same as uniform heating if

\[
\text{erfc} \left( \frac{a}{2\sqrt{\alpha t}} \right) \ll 1
\]

- This is true for \( \text{erfc}(>1) \) thus

\[
t < \frac{a^2}{4\alpha}
\]

- eg for Copper with \( a = 1 \text{ mm} \) and \( \alpha = 1.16 \times 10^{-4} \text{ m}^2/\text{s} \),

\[
t < \frac{\left(10^{-3}\right)^2}{4\left(1.16 \times 10^{-4}\right)} \quad \text{or} \quad t < 2.16 \times 10^{-3} \text{ s}
\]

![Figure 12-2  Laser beam focused on a workpiece.](image)
Laser Focused into a Spot

• As $t$ goes to infinity (very long times) it can be shown

$$\Delta T(z,t) = \frac{H}{k} \left[ \sqrt{z^2 + a^2} - z \right]$$

• Thus for finite spot temperature reaches a limit
• Highest surface temp

$$\Delta T(0, \infty) = \frac{Ha}{k}$$

• Effects of beam Gaussian distribution is not that different
• In practice as thermal conductivity $k$, reflectance $R$, thermal diffusivity $\alpha$ all vary with temperature
• Thus tend to use numerical simulations for real details

![Diagram of laser beam focused on a workpiece.](image)
Example 5.1 Estimated temperature rise during a heat pulse

Suppose a heat pulse of duration $t_p$ falls onto a metal surface. We may estimate the depth ($L_p$) to which the heat will diffuse in a time $t_p$ by using Eq. (5.3); thus

$$L_p = 2\sqrt{\alpha t_p}$$

Considering a unit cross-sectional area of the material, the heated volume is $L_p \times 1$ and the total amount of heat deposited during the pulse is $H t_p$, where $H$ is the (constant) heat flow per unit area during the pulse. Assuming that the heat is uniformly deposited throughout the heated volume, the average temperature rise is $H t_p / m C$, where $m$ is the mass of the heated volume. Now $m = L_p \rho$, where $\rho$ is the material density, and we may replace $\rho C$ by $K/\alpha$. Thus the final result for the average temperature rise is

$$\Delta T = \frac{H t_p \alpha}{L_p K} = \frac{H}{2K} \sqrt{\alpha t_p}.$$  

We may apply this to the situation dealt with in Fig. 5.4. Substituting $H = 10^{10} \text{ W m}^{-2}$, $t_p = 10^{-6} \text{ s}$, $K = 385 \text{ W m}^{-1} \text{ K}^{-1}$, $\alpha = 10^{-4} \text{ m}^2 \text{ s}^{-1}$ gives

$$\Delta T = 135^\circ \text{C}.$$  

We see that this result is in reasonable agreement with the more exact analysis illustrated in Fig. 5.4.
Phase Changes and Energy Balance

• Energy Balance:
  Energy in = Energy to raise temp + heat flow

• Note: a rough rule of thumb if near steady state
  half the energy goes into heat flow
  so energy required is twice that to raise temperature

• As heating increase will get melting of the surface
• Eventually also get vaporization point
• All requires energy to heat

• In general the specific heat of the material changes
  \( C_s = \) specific heat of solid
  \( C_l = \) specific heat of liquid phase
  \( L_f = \) Latent Heat of Fusion: energy for melting
  \( L_v = \) Latent Heat of Vaporization: energy to vaporize

• Energy required to melt a unite volume of material
  \[ E_m = \rho \left[ C_s (T_m - T) + L_f \right] \]

  where \( T_m \) is the melting point,
  \( T \) the starting temp.
  \( \rho \) = density of material

• Note: this does not include energy lost to heat flow
Phase Changes and Energy Balance

- When vaporization occurs
  \[ E_v = \rho \left[ C_s (T_m - T) + C_v (T_v - T_m) + L_f + L_v \right] \]

- Generally true that heat capacity does not change much with T
  \[ C_m \approx C_v \approx C \]

- Generally Latent heat of vapourization >heat of fusion
  \[ L_f < L_v \]

- Vapourization temperature is much < base or melting
  \[ T < T_m < T_v \]

- Energy input required is approximately
  \[ E_v \approx \rho \left( C T_v + L_v \right) \]

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity (W m⁻¹ K⁻¹)</th>
<th>Thermal diffusivity (m² s⁻¹) (10⁻⁴)</th>
<th>Specific heat capacity (J kg⁻¹ K⁻¹)</th>
<th>Density (kg m⁻³)</th>
<th>Melting point (T_m) (K)</th>
<th>Boiling point (T_v) (K)</th>
<th>Latent heat of vaporization (L_v) (J kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>238</td>
<td>97.3</td>
<td>903</td>
<td>2710</td>
<td>932</td>
<td>2720</td>
<td>10.90</td>
</tr>
<tr>
<td>Copper</td>
<td>400</td>
<td>116.3</td>
<td>385</td>
<td>8960</td>
<td>1356</td>
<td>2855</td>
<td>4.75</td>
</tr>
<tr>
<td>Iron</td>
<td>82</td>
<td>23.2</td>
<td>449</td>
<td>7870</td>
<td>1810</td>
<td>3160</td>
<td>6.80</td>
</tr>
<tr>
<td>Mild steel</td>
<td>45</td>
<td>13.5</td>
<td>420</td>
<td>7860</td>
<td>1700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stainless steel (304)</td>
<td>16</td>
<td>4.45</td>
<td>460</td>
<td>7818</td>
<td>1700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>90</td>
<td>22.8</td>
<td>444</td>
<td>8900</td>
<td>1726</td>
<td>3110</td>
<td>6.47</td>
</tr>
<tr>
<td>Silver</td>
<td>418</td>
<td>169</td>
<td>235</td>
<td>10500</td>
<td>1234</td>
<td>2466</td>
<td>2.31</td>
</tr>
<tr>
<td>Alumina (ceramic)</td>
<td>28</td>
<td>9.54</td>
<td>800</td>
<td>3600</td>
<td>2000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perspex</td>
<td>0.2</td>
<td>0.11</td>
<td>1500</td>
<td>1190</td>
<td>350</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silicon</td>
<td>170</td>
<td>103</td>
<td>707</td>
<td>2630</td>
<td>1680</td>
<td>2628</td>
<td>10.6</td>
</tr>
</tbody>
</table>

†Measured at 300 K, values fairly strongly temperature dependent.
Melting Depths

- Consider light pulse on surface
- Will get melting to some depth
- Eventually also get surface at vaporization point
- This is the laser welding situation
- Can estimate the depth of melt front after some time \( t \)
- Recall temperature distribution

\[
\Delta T(z,t) = \frac{2H}{k} \sqrt{\alpha t} \text{erfc} \left[ \frac{z}{2\sqrt{\alpha t}} \right]
\]

- Ratio of the Temperatures changes with depth are

\[
\frac{\Delta T(z,t)}{\Delta T(0,t)} = \sqrt{\pi} \text{erfc} \left[ \frac{z}{2\sqrt{\alpha t}} \right]
\]

- Eventually surface rises to vaporization point
- It cannot rise higher without vaporization thus stays at \( T_v \)
- Hence can calculate the melt pool depth with this.

---

**Figure 12-3** Vapor front propagation in a solid.
Melt Depth Estimate

- Estimate the depth of melt front for that after some time $t$
- Bottom of melt is at melting point, Top at vapourization point and assume base temperature is near $0^\circ$C (ie ~room temp)

$$\Delta T(z,t) = T_m \quad \Delta T(0,t) = T_v$$

$$\frac{T_m}{T_v} = \sqrt{\pi} \operatorname{ierfc} \left[ \frac{z}{2\sqrt{\alpha t}} \right]$$

- Recall that at the surface

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

- Thus time can be eliminate by solving for

$$T_v \frac{k\sqrt{\pi}}{2H} = \sqrt{\alpha t}$$

- Depth of melt is given by

$$\operatorname{ierfc} \left[ \frac{z_m H}{T_v k\sqrt{\pi}} \right] = \frac{T_m}{T_v \sqrt{\pi}}$$

- Note: for a given material $H z_m$ is fixed
- Thus large welding depths given by low heat intensities applied for long time provided that there is sufficient energy in the beam
Example of Melting Calculations

• What is the heat flow required for weld depth of 0.1mm in copper

• From the table for copper
  \( T_m = 1060 \, ^\circ C \)
  \( T_v = 2570 \, ^\circ C \)
  \( K = 400 \, \text{W/m}^\circ \text{C} \)

• Thus

\[
\text{ierfc} \left[ \frac{z_m H}{T_v k \sqrt{\pi}} \right] = \frac{T_m}{T_v \sqrt{\pi}} = \frac{1060}{2570 \sqrt{\pi}} = 0.232
\]

• From the graph or calculation

\[ \text{ierfc}(x=0.44) = 0.232 \]

• Thus

\[
H = \frac{T_v k \sqrt{\pi}}{z_m} = \frac{400(2570) \sqrt{\pi}(0.44)}{0.0001} = 8 \times 10^9 \, \text{W/m}^2
\]
Vaporization of Material

- When material removed by vaporization
- Get a melt front and a heated front
- Liquid front moves with velocity $v_s$
- From the heat balance, assume that all power goes into heating
- Then the melt front should be

$$H \approx v_s \rho \left( C T_v + L_v \right)$$

where $H$ is power density per square area
- Note this is the minimum power value
- Good rule of thumb is actual power required twice this loss about the same by heat flow to substrate
- Can calculate depth $d_v$ of holes by knowing laser pulse duration $t_p$ and front velocity

$$d_v = v_s t_p$$

Figure 12-3  Vapor front propagation in a solid.
Example Depth of Hole with Vaporization

- Heat pulse of $H = 10^{11} \text{ W/m}^2$ and $t = 500 \text{ microsec}$ hits copper. What will be the resulting max hole depth

- From the tables
  
  $T_v = 2570 \, ^\circ\text{C}$
  
  $\rho = 8960 \, \text{kg/m}^3$
  
  $C = 385 \, \text{J/kg}^\circ\text{C}$
  
  $L_v = 4.75 \times 10^6 \, \text{J/kg}$

\[
 d_v = \frac{H t_p}{\rho (C T_v + L_v)} = \frac{10^{11}(5 \times 10^{-4})}{8960(385[2570] + 4.75 \times 10^6)}
\]

\[
= 0.95 \times 10^{-3} \, \text{m} = 0.95 \text{mm}
\]

---

Table 5.1

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal conductivity(\text{t}^{\dagger}) (W m(^{-1}) K(^{-1}))</th>
<th>Thermal diffusivity (\alpha) (10^{-6}) m(^2) s(^{-1})</th>
<th>Specific heat capacity (C) (J kg(^{-1}) K(^{-1}))</th>
<th>Density (\rho) (kg m(^{-3}))</th>
<th>Melting point (T_m) (K)</th>
<th>Boiling point (T_b) (K)</th>
<th>Latent heat of vaporization (L_v) (J kg(^{-1})) (10(^6))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>238</td>
<td>97.3</td>
<td>903</td>
<td>2710</td>
<td>932</td>
<td>2720</td>
<td>10.90</td>
</tr>
<tr>
<td>Copper</td>
<td>400</td>
<td>116.3</td>
<td>365</td>
<td>8960</td>
<td>1356</td>
<td>2855</td>
<td>4.75</td>
</tr>
<tr>
<td>Iron</td>
<td>82</td>
<td>23.2</td>
<td>449</td>
<td>7870</td>
<td>1810</td>
<td>3160</td>
<td>6.80</td>
</tr>
<tr>
<td>Mild steel</td>
<td>45</td>
<td>13.6</td>
<td>420</td>
<td>7860</td>
<td>1700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stainless steel</td>
<td>(304)</td>
<td>16</td>
<td>4.45</td>
<td>7818</td>
<td>1700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>90</td>
<td>22.6</td>
<td>444</td>
<td>8900</td>
<td>1726</td>
<td>3110</td>
<td>6.47</td>
</tr>
<tr>
<td>Silver</td>
<td>418</td>
<td>169</td>
<td>235</td>
<td>10500</td>
<td>1234</td>
<td>2466</td>
<td>2.31</td>
</tr>
<tr>
<td>Alumina (ceramic)</td>
<td>28</td>
<td>9.54</td>
<td>800</td>
<td>3900</td>
<td>2300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Perspex</td>
<td>0.2</td>
<td>0.11</td>
<td>1500</td>
<td>1190</td>
<td>350</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silicon</td>
<td>170</td>
<td>103</td>
<td>707</td>
<td>2330</td>
<td>1680</td>
<td>2628</td>
<td>10.6</td>
</tr>
</tbody>
</table>

\(\dagger\) Measured at 300 K, values fairly strongly temperature dependent.
Keyholes and Increased Welding/Cutting Depths

- When the laser forms hole in material
- Beam penetrates to much greater depth
- Creates a large deep melt pool behind moving beam
- Melt fills in hole behind moving beam
- If not true welding limited 1 mm in steel

Fig. 5.15 Formation of a 'keyhole' during high-power laser welding.
Keyholes Formulas

- Modeled by Swift Hook and Gick, 1973
- Assume linear heat source power P (W)
- Note P is total power while H is unreflected power because keyhole absorbs all the power (reflections do no escape)
- Extends into metal depth a
- Moving forward with velocity v (weld speed) in direction y direction across weld is x (centred on the heating point)
- Temperature distribution becomes

\[
T = \frac{P}{2\pi ak} \exp \left( \frac{vx}{2\alpha} \right) K_0 \left( \frac{v\alpha \sqrt{x^2 + y^2}}{2} \right)
\]

- where \( K_0 \) is the Bessel function 2nd kind order 0
- Width w of the weld is given by the point where \( T = \text{melting} \)

\[
w \approx 0.484 \frac{\alpha}{v \, akT_m} P
\]

Figure 12-5  Linear heat source model of laser keyholing. (Courtesy of Optical Engineering and United Technologies Research Center.)
Laser Machining Processes

- Laser heat processing divided into 3 regions
- Heating
- Melting
- Vaporization

Fig. 6.1. Range of laser processes mapped against power density per unit time.
Laser Surface Treatment

Annealing or Transformation Hardening
• surface hardness

Surface Melting
• homogenization, recrystallization

Alloying
• changing surface composition
• improves corrosion, wear or cosmetic properties

Cladding
• Applying a different material to surface
• improves corrosion, wear or cosmetic properties

Texturing
• changing surface appearance

Plating
• By Chemical Vapor Deposition
Laser Annealing

- Uses the rapid, local, high temperature, heating and cooling (quenching)
- Materials where heating with quenching changes characteristics
- Best examples: Iron/Steel
- With laser can make local changes in material parameters
- Increase hardness, strength
- Temper (make more ductile)

Fig. 6.4. Experimental arrangement for laser heat treatment.
Comparison of Material Heating Processes

<table>
<thead>
<tr>
<th>1. Heating Processes</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser</td>
<td>Minimum part distortion</td>
<td>High equipment cost</td>
</tr>
<tr>
<td></td>
<td>Selective hardening</td>
<td>Coverage area restricted</td>
</tr>
<tr>
<td></td>
<td>No quenchant required</td>
<td>Absorbent coatings necessary</td>
</tr>
<tr>
<td></td>
<td>Thin case capability</td>
<td>Multiple passes give local</td>
</tr>
<tr>
<td></td>
<td>Case depth controllable</td>
<td>tempering</td>
</tr>
<tr>
<td></td>
<td>Eliminates post processing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Improves fatigue life</td>
<td></td>
</tr>
<tr>
<td>Induction</td>
<td>Fast process rates</td>
<td>Downtime for coil change</td>
</tr>
<tr>
<td></td>
<td>Deep case obtainable</td>
<td>Quenchant required</td>
</tr>
<tr>
<td></td>
<td>Lower capital cost than laser</td>
<td>Part distortion</td>
</tr>
<tr>
<td></td>
<td>Coverage area</td>
<td>Coil placement critical</td>
</tr>
<tr>
<td>Flame</td>
<td>Cheap, flexible and mobile process</td>
<td>Large thermal penetration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EM forces may spoil surface</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fabrication of complex coils for specific</td>
</tr>
<tr>
<td></td>
<td></td>
<td>processes</td>
</tr>
<tr>
<td>Arc (TIG)</td>
<td>Relatively cheap and flexible process</td>
<td>Section thickness limited</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large thermal penetration</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stirring takes place</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Poor control to avoid melting</td>
</tr>
<tr>
<td>Electron beam</td>
<td>Minimal distortion, selective</td>
<td>High equipment cost</td>
</tr>
<tr>
<td></td>
<td>hardening and no quenchant required</td>
<td>Requires vacuum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low production rate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High processing costs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2. Thermochemical Diffusion Processes</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Carburising</td>
<td>Conventional &lt; 950°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High temperature &gt; 950°C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low pressure (&quot;vacuum&quot;)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N₂-based carrier gas</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fluidised bed</td>
<td></td>
</tr>
<tr>
<td>Nitriding</td>
<td>Conventional</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ion nitriding</td>
<td></td>
</tr>
<tr>
<td>Carbonitriding (austenitic)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 6.3. Chart of Competing Processes for Heat Treatment.