Laser Bending

ME 677: Laser Material Processing
Instructor: Ramesh Singh

Outline

- Process Descriptions
- Mechanisms of Laser Bending
- Applications

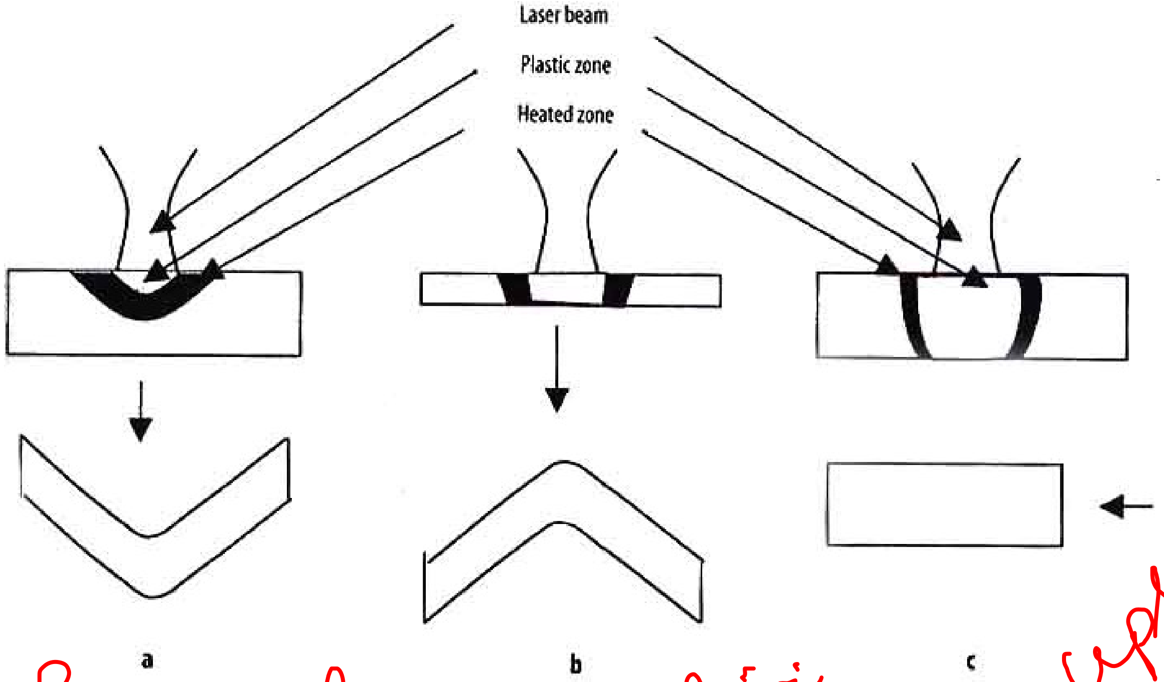
Introduction

- Deformation can be induced in a controlled manner in sheets and plates by tracking the laser beam across one side of the material
- Temperature gradients are developed through the material thickness which induce stresses because of the differential expansion of adjacent layers that are at different temperatures
- Materials such as stainless steels and the light alloys of aluminum, magnesium and titanium have a high coefficient of thermal expansion such sheet materials can deform significantly when laser heated
- The most important beam variables are the energy absorbed per unit length, the configuration of the heating source and the treatment sequence

Principal Mechanisms

- Temperature gradient mechanism
- The point source mechanism
- Buckling mechanism
- Upsetting mechanism

Mechanism of Bending



Thermal gradient

Buckling

upsetting

Thermal Gradient Mechanism

- The material is heated by the laser such that there is a steep thermal gradient through the thickness
- The material will be under compression due to restraint caused by the material underneath which is still cold
- Plastic flow will occur in the surface region provided the temperature is high enough to cause thermal strain
- The plastic strain will not be recovered during cooling

Thermal Gradient

- Due to cooling the rest of material will heat up a little via conduction, causing a reduction in tensile stresses in the cooler region
- Finally, the area over which the stresses operate during cooling are redistributed to the whole sheet as opposed to the small zone
- The plastic deformation due to heating is not recovered and the piece bends towards laser on cooling

Thermal Depth in Bending

- To create this thermal gradient implies that a laser beam must traverse the workpiece moving at such a speed that the thermal depth, z, is small compared to the workpiece depth s_0

$$Fourier no = 1$$

$$\frac{z^2}{\alpha t} = 1$$

$$z^2 << s_0^2$$

$$\alpha t << s_0^2$$

$$\frac{\alpha t}{s_0^2} << 1$$

$$t = D/V$$

$$\frac{\alpha D}{V s_0^2} << 1$$

t = interaction time

D = Beam Dia

V = Scan Velocity

$z << S_0$

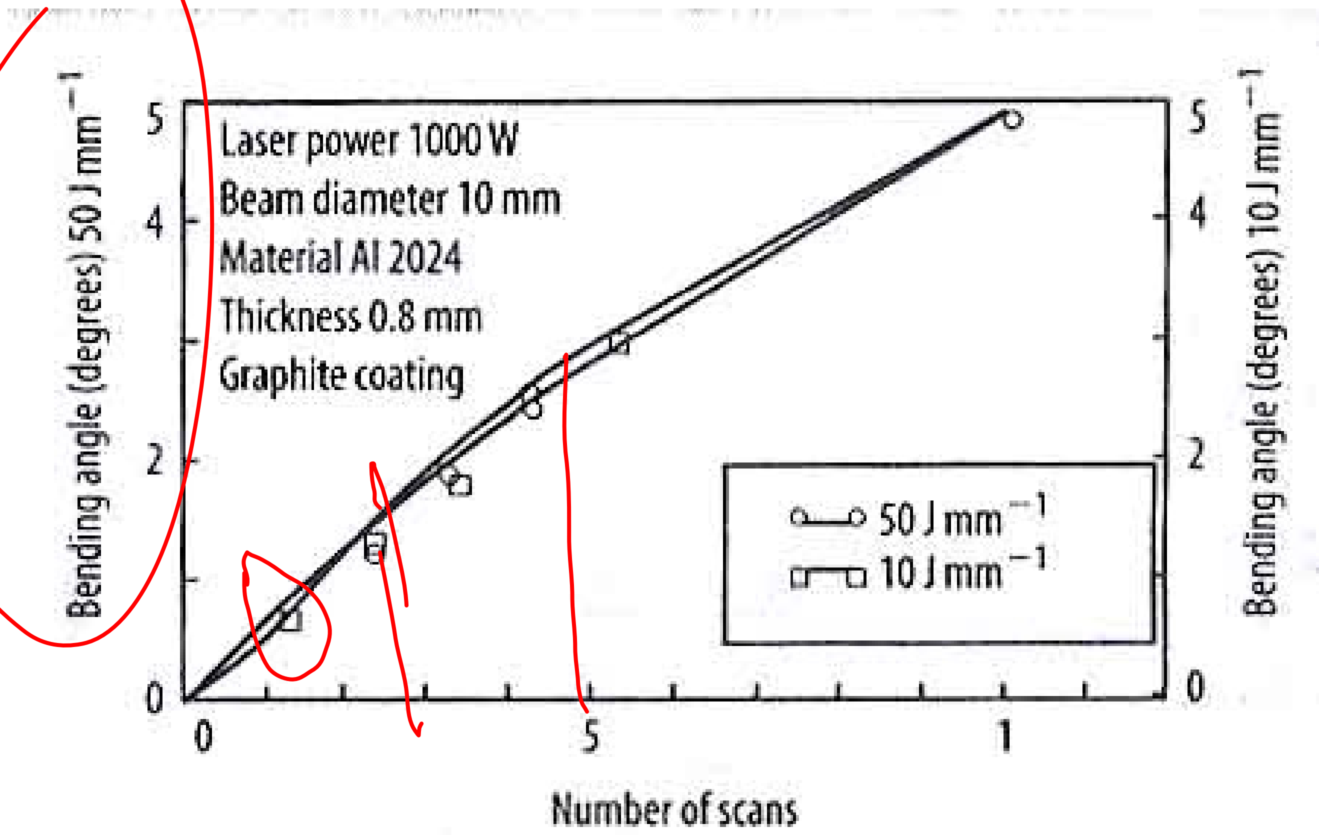
ensures thermal gradient

$$\frac{z^2}{\alpha t} = 1$$

Thermal Gradient Bending

- The bending is asymmetric
  - The restraint is not same at edges and the middle of the sheet
  - The previously heated region cools and contract causing a bend at that location while the beam is heating at some other location
- The amount of bending per pass is not very great, 1-3 deg

Bending Angle

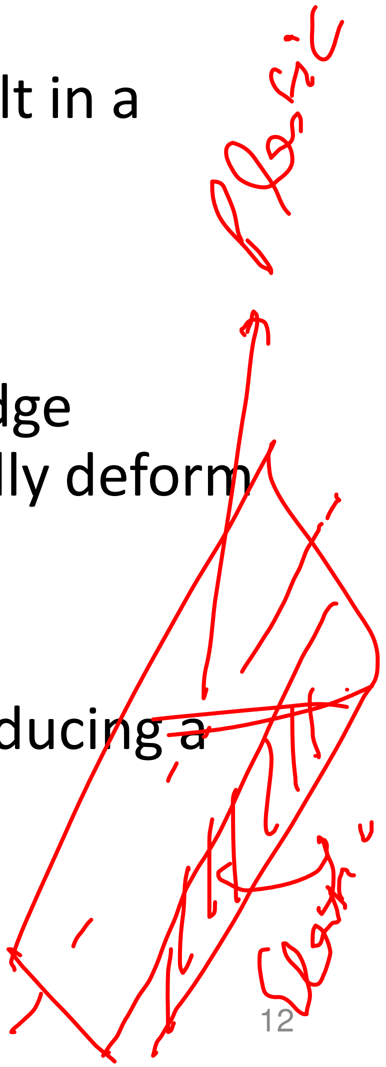


Point Source Mechanism

- If the beam source is stationery then the heated zone is a spot rather than a line
- For a brief pulse thermal gradient will be created and the mechanism is similar to thermal gradient
- The mechanical bend differs due to the shortened spot resulting in pucker on the surface and finally bend along the line of least resistance (smallest width)
- If the pulse width is longer then it could result in buckling mechanism
- It is used for micro-components and bending angle is 1/10 - 1/100 of a degree

Buckling Mechanism

- If there is little thermal gradient through the depth of the sheet then the gradient mechanism will not work
- Expansion resulting from through heating will result in a bulge
- This bulge can move upwards or downwards
  - initial bend; residual stress, applied stress
- The center of bulge is hotter than the edges: the edge deformation will be elastic but center will plastically deform
- On cooling the plastic bend remains
- The rate of bending is 1-15 deg per pass
- The direction of bending could be ensured by introducing a bias



Upsetting Mechanism

- If the material geometry does not allow for buckling due to its thickness or section modulus the no buckling is restrained
- The laser treatment produces a thermal field with no significant gradient, plastic deformation through the thickness will occur beyond a particular temperature
- The material will be thickened which does not recover even after cooling

Modeling Thermal Gradient-Trivial or Two Layer Model

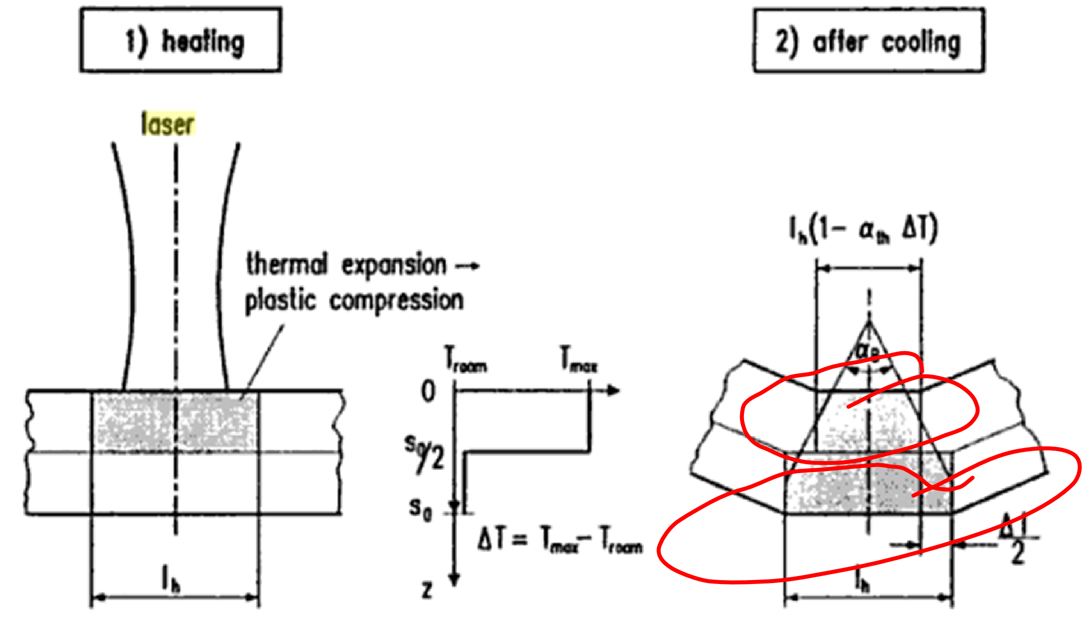


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Fig. 6.27 A trivial model for laser bending.

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Assumptions

- Temperature field is a step function
- All thermal expansion is converted to plastic flow
- No mechanical strain
- The bending is purely due to geometry

AP = Total power

$$AP = \rho\, C_p\, \Delta T\, \dot{V}$$

$\dot{V}$ = volume/sec

$$\dot{V} = l\, v\, \delta_0$$

δ_0 → thickness

v → velocity

$$AP = \frac{\rho \cdot v \cdot l \delta_0 C_p \cdot \Delta T}{2}$$

Heating is only in top layer

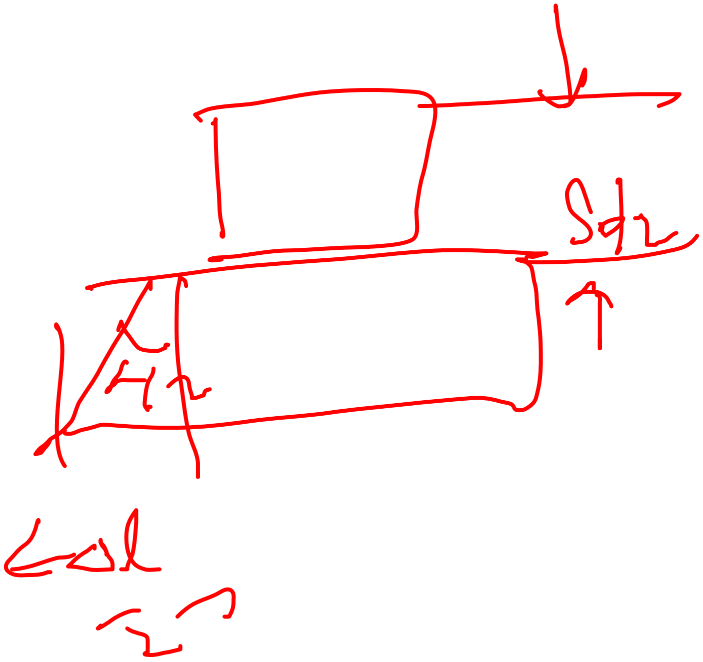
$$\Delta T = \frac{2 \cdot A \cdot P}{\rho v l \delta_0 C_p}$$

$$\delta l = l \cdot \alpha_{th} \cdot \Delta T$$

$$= 2 \cdot AP \cdot \alpha_{th} / \rho v \, \delta_0 C_p$$

$$\delta l = \frac{2A \cdot P\, \alpha_{th}}{\rho v \delta_0 c_p}$$

$$\tan\left(\alpha/2\right) = \frac{\delta l/2}{\delta_0/2}$$



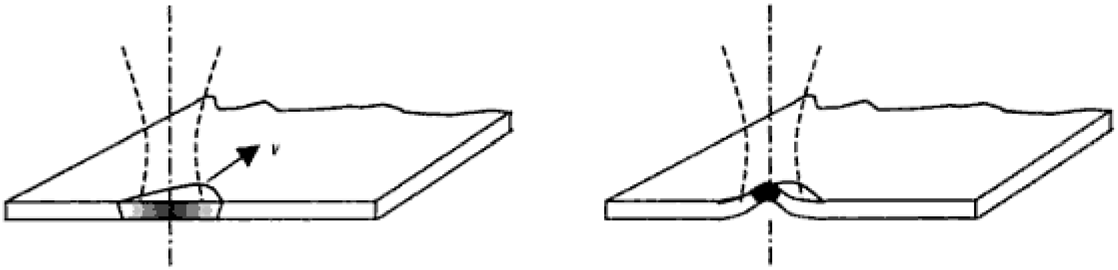
$$\tan(\alpha/2) = \delta l/\delta_0$$

$$\alpha/2 = \frac{\delta l}{s_0}$$ (For small α or bend angles)

$$\alpha/2 = \frac{2 \cdot A \cdot P \alpha_{th}}{\rho v s_0^2 C_p}$$

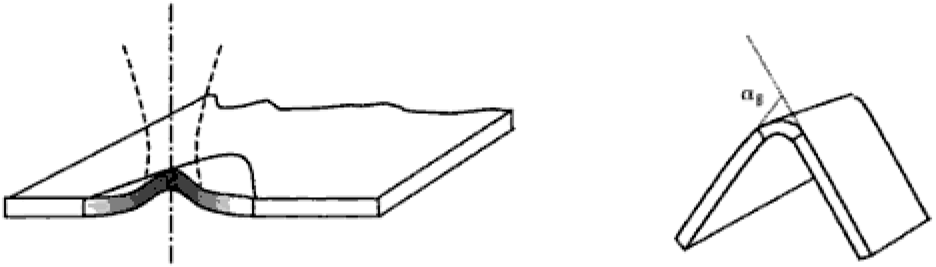
$$\boxed{\alpha = \frac{4 \cdot A \cdot P \alpha_{th}}{\rho v s_0^2 C_p}} \rightarrow \text{Bend Angle.}$$

Modeling of Buckling Mechanism



Stage 1: heating

Stage 2: bulging



Stage 3: growth of buckle

Stage 4: cooling and formation of bend

Figure 8.7 The stages in the development of a buckle (after Vollertsen[7]).

Buckling Drawing

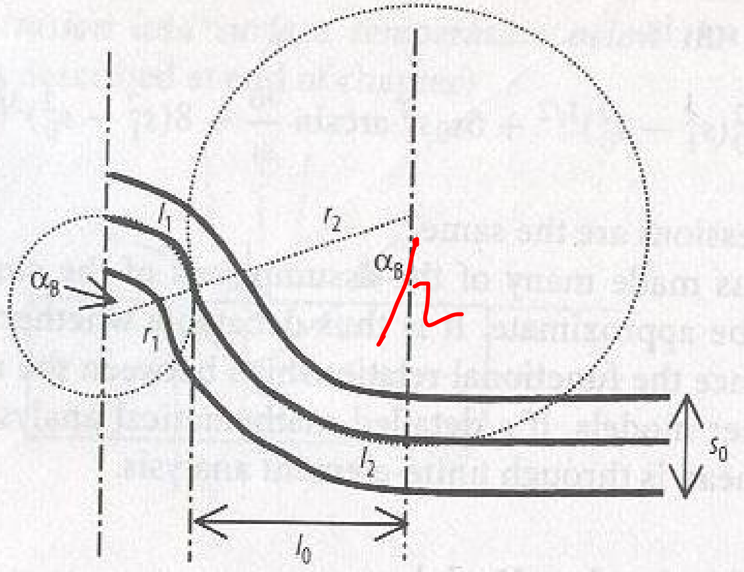


Figure 8.8 Two-dimensional representation of a buckle at stage 3.

$$\frac{\alpha_B}{2} = \frac{l_1}{r_1} = \frac{l_2}{r_2}$$

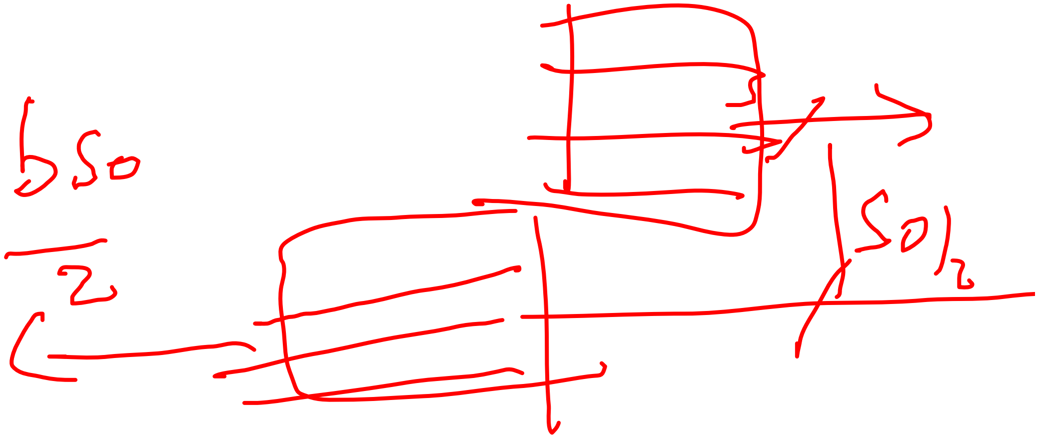
$\epsilon = -Ky$ (From beam bending)

$$\sigma = E-Ky$$

$$M = \int \sigma \cdot dA \cdot y = \int -Eky^2 dA$$

$$M_c = \frac{E b \delta_0^3}{12 R_2} \quad \text{— (i)}$$

$$M_p = K_f(T_1) . \frac{\delta_0}{2} . \frac{b \delta_0}{2}$$



where $K_f(T_1)$ is flow stress

$$= K_f(T_1) . b \delta_0^2 /4 \quad \text{— (ii)}$$

Calculate the value of r_2

$$r_2 = \frac{E S_0}{3 K_f(T_1)}$$

$$l_{o_2} = r_2 \sin(\alpha/2)$$

$$\Delta l = \alpha_{th} \Delta T_{av} \cdot l_h$$

$$\Delta T_{av} = \frac{1}{2} A \cdot P / \rho \cdot l \cdot S_0 C_p v$$

$$\Delta l = \alpha_{th} \cdot \Delta T_{av} \cdot l_h$$

$$\Delta T_{av} = \frac{A \cdot P}{2 C_p \rho \delta_o \cdot v l_h}$$

$$\Delta l = \frac{A \cdot P \cdot \alpha_{th}}{2 C_p \rho \delta_o v}$$

$$l_{o_2} = r_2 \sin(\alpha_B/2)$$

$$l_2 = r_2 \sin(\alpha_B/2) + \frac{A \cdot P \alpha_{th}}{2 c_p \rho \delta_0 v}$$

$$\frac{\alpha_B}{2} = \sin(\alpha_B/2) + \frac{A P \alpha_{th} \cdot f'}{2 c_p \rho \delta_0 \cdot v \cdot r_2}$$

$$\frac{\alpha_B}{2} = \frac{\alpha_B}{2} - \left(\alpha_B/2\right)^3 \frac{1}{3!} + \frac{A P \alpha_{th}}{2 c_p \rho \delta_0}$$

$$\cancel{\frac{\alpha_B}{2}} = \cancel{\frac{\alpha_B}{2}} - \frac{\alpha_B^3}{48} + \frac{A P \alpha_{th} f(\ \xrightarrow{} 0.5}{2 c_p \rho s_0 v h_2}$$

$$\frac{\alpha_B^3}{48} = \frac{A P \alpha_{th} \cdot K_f(T) \cdot 3}{4 c_p \rho s_0 \cdot v E s_0}$$

$$\alpha_B =$$

$$x_B = \left(\frac{36\,\alpha_{th}\, A.P.\, K_f(T_1)}{C_p\, \rho\, r_b^2\, E\, v} \right)^{1/3}$$

Upsetting Mechanism

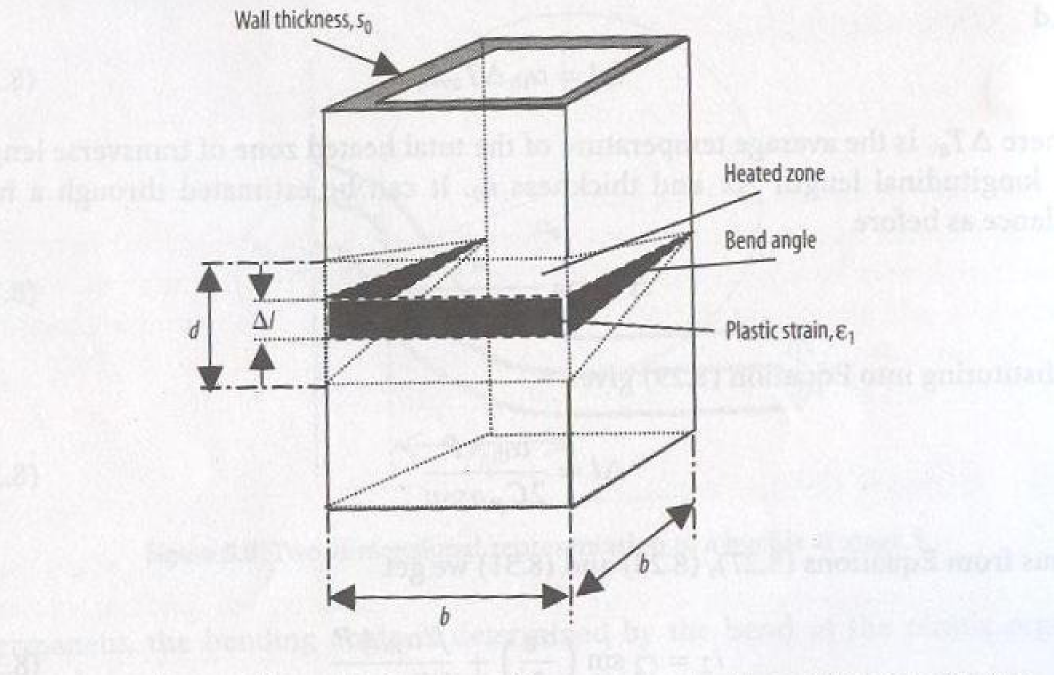


Figure 8.9 Diagram illustrating bending of an extrusion by the upsetting mechanism.

APPLICATIONS

- Non contact bending
- Bend is stronger that the parent sheet
- Bending of pipes and extrusions
- A forming tool for astronauts
- Adjustment of sealed electric contacts
- Straightening of rods

Practice Problem

- Approximate a first order mathematical expression for following three mechanisms of bending and use reasonable values for the variables to predict the bend angles in:
  - Thermal gradient
  - Buckling
  - Upsetting