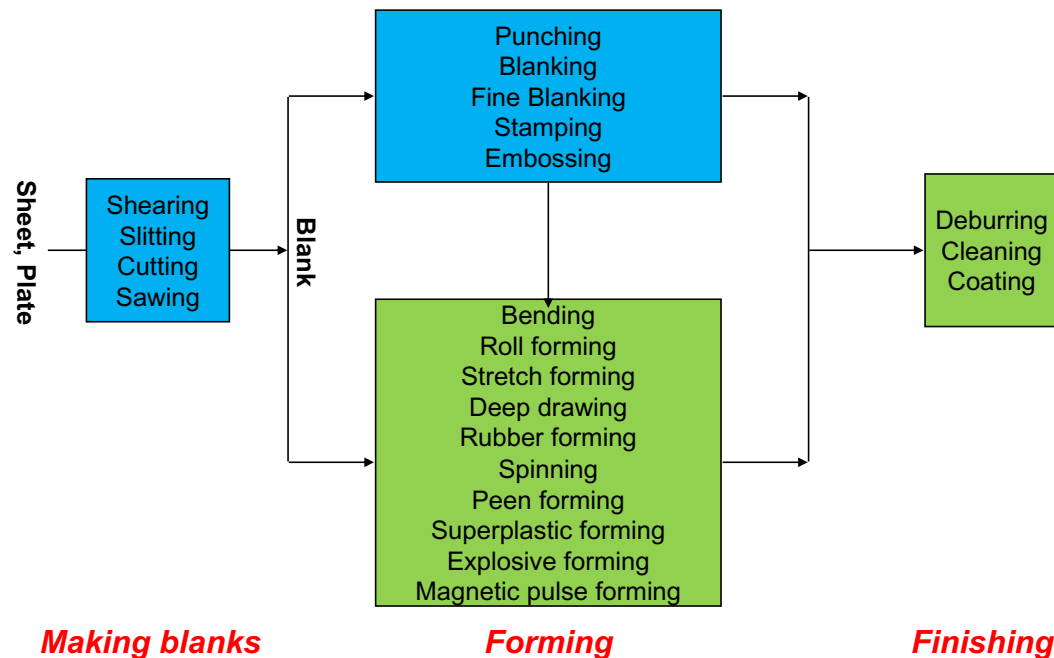


Sheet Forming Processes

Chapter 7

Sheet forming practice

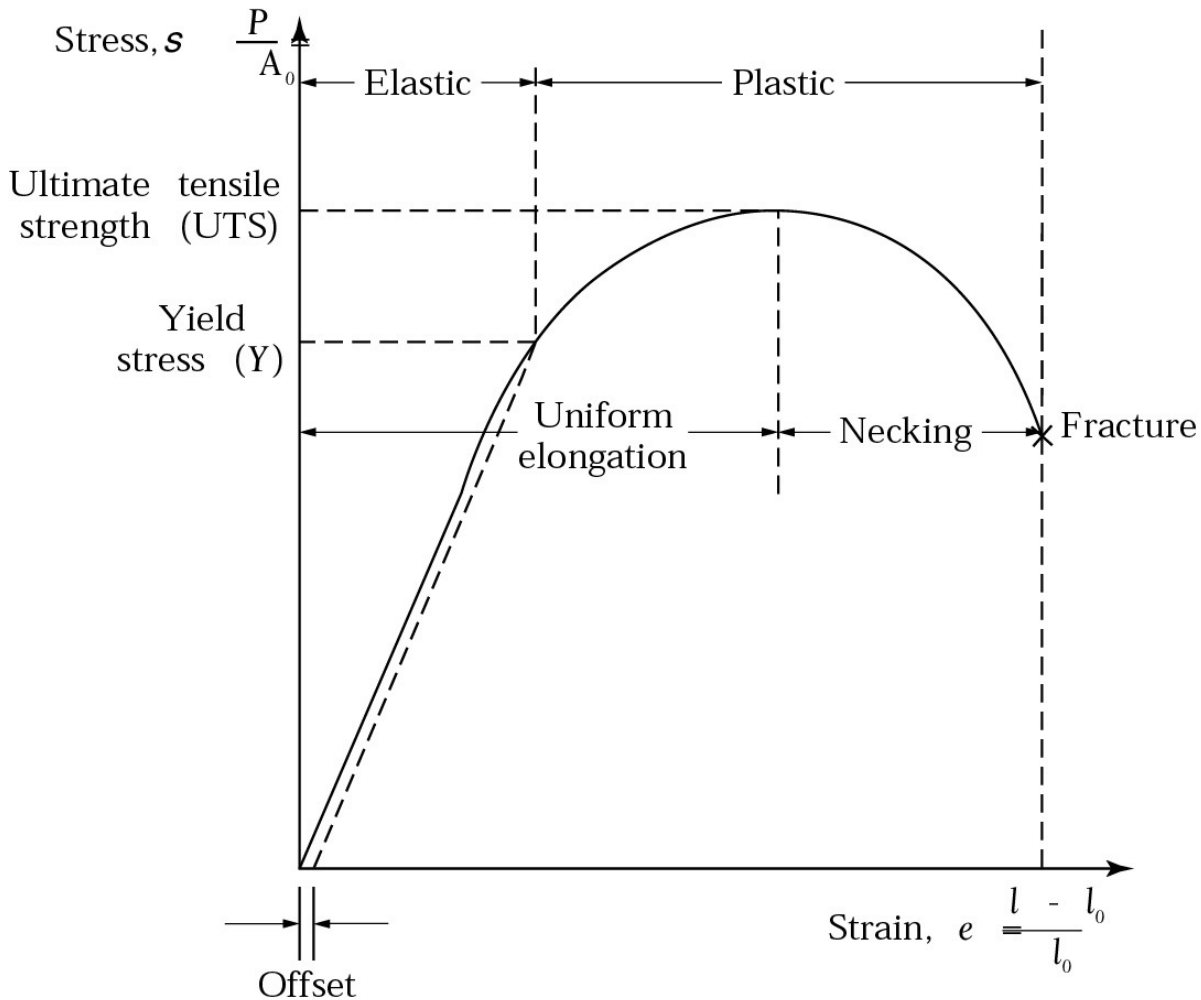
- Most common commercial materials are *carbon steels*
- *Aluminum* and *titanium alloys* more and more used
- Sheet metal forming consists of three basic processes:
 - **Cutting to form a shape (blank)**
 - **Forming by bending, stretching and deep drawing**
 - **Finishing**



General characteristics

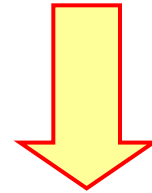
- Metal sheets are characterized by a *high* ratio between the surface area and thickness
 - Forming of sheets is carried out by tensile forces in the plane of the sheet
 - Thickness decrease should be generally avoided, as it can lead to necking and fracture
-
- **Advantages**
 - light weight
 - versatile shapes
 - low cost processes
 - **Disadvantages**
 - tooling costs (suitable for high production runs)

Elongation



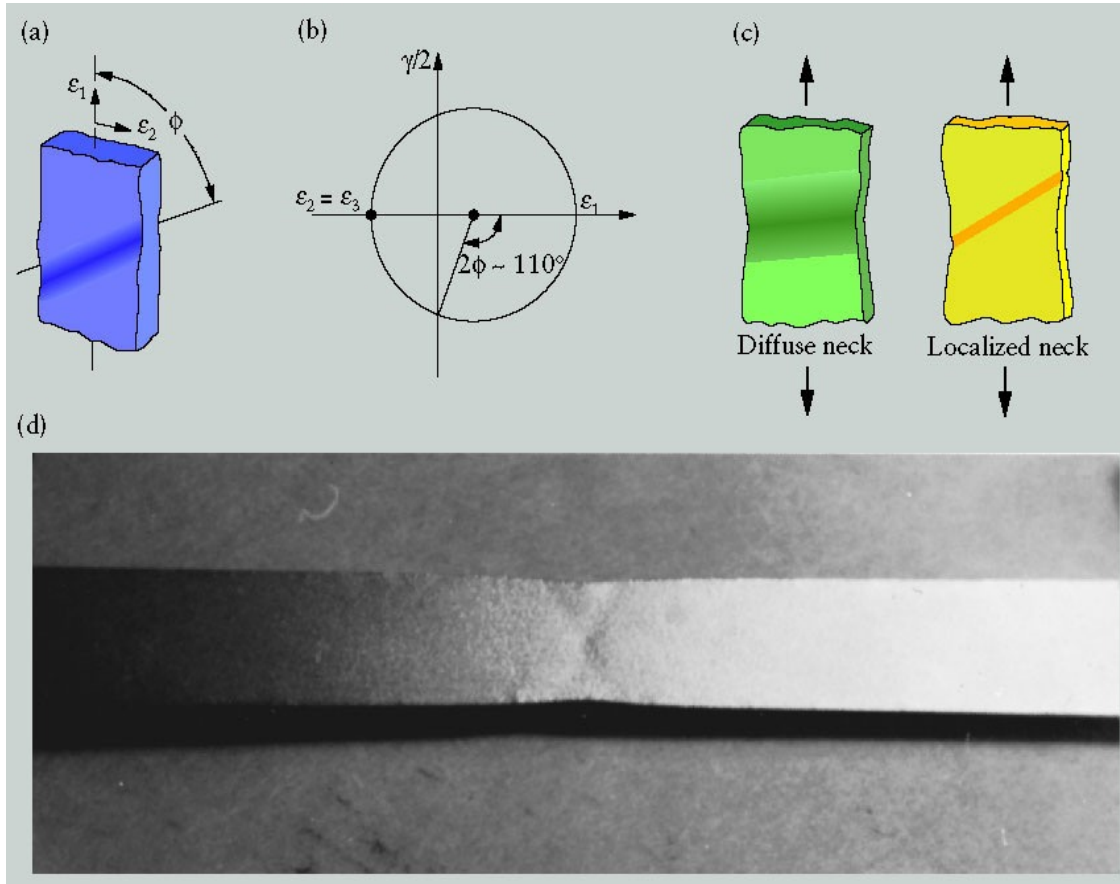
$$\sigma = K\varepsilon^n$$

$$\varepsilon_{necking} = n$$



A large value of n
indicates good
formability

Localized vs. diffuse necking



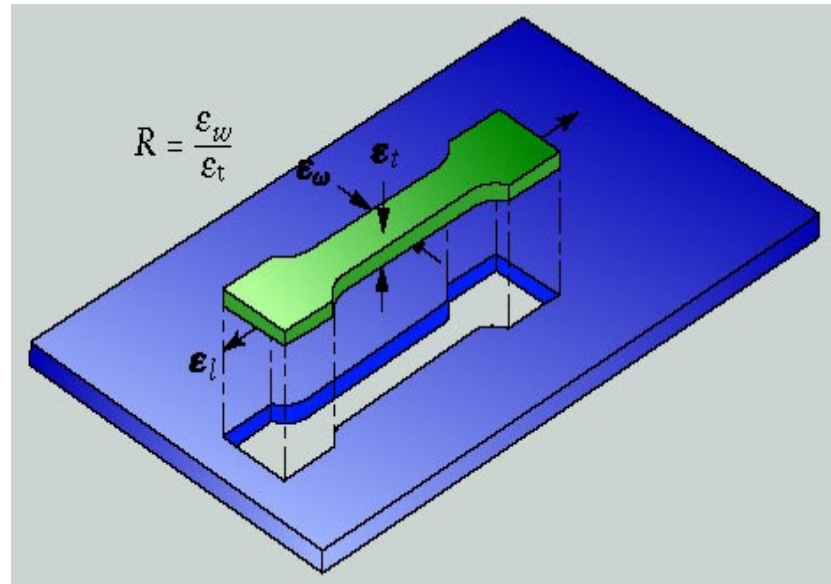
Whether necking is localised or diffuse depends on the strain-rate sensitivity m ; the higher the value of m , the more diffuse the neck becomes.

Good formability: high uniform elongation + high post-uniform elongation

→ $n \uparrow \uparrow$ $m \uparrow \uparrow$

Normal anisotropy

$$R = \frac{\varepsilon_w}{\varepsilon_t} = \frac{\ln\left(\frac{w_0}{w_f}\right)}{\ln\left(\frac{t_0}{t_f}\right)}$$



Average normal anisotropy

$$\bar{R} = \frac{R_0 + 2R_{45} + R_{90}}{4}$$

Average normal anisotropy

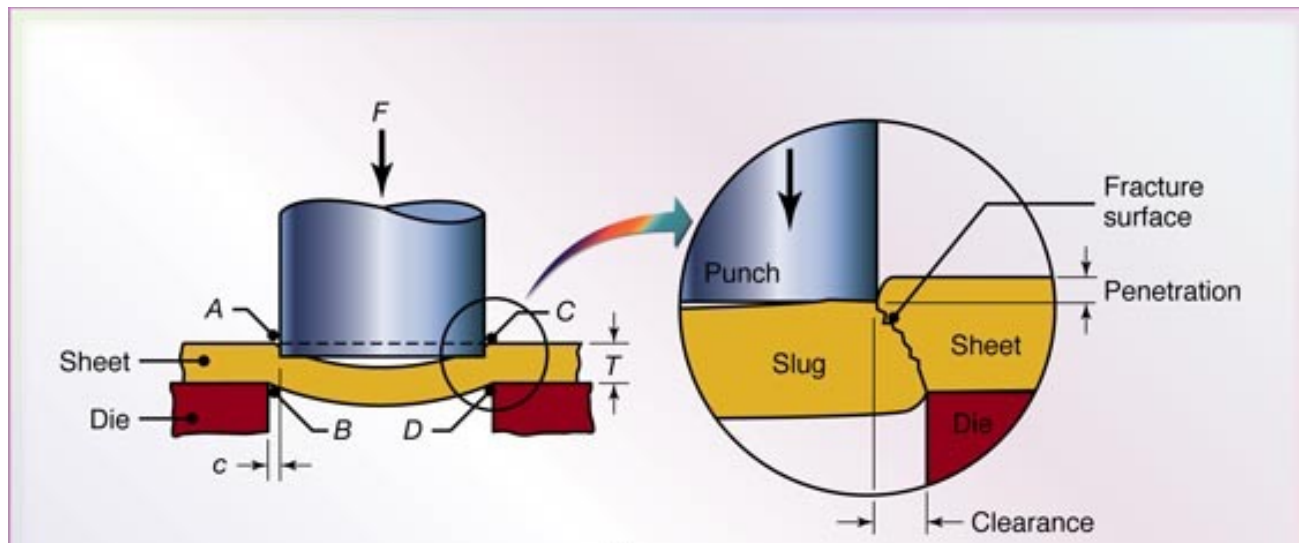
TABLE 16.4

**Typical Ranges of Average Normal Anisotropy,
 R_{avg} , for Various Sheet Metals**

Zinc alloys	0.4–0.6
Hot-rolled steel	0.8–1.0
Cold-rolled, rimmed steel	1.0–1.4
Cold-rolled, aluminum-killed steel	1.4–1.8
Aluminum alloys	0.6–0.8
Copper and brass	0.6–0.9
Titanium alloys (α)	3.0–5.0
Stainless steels	0.9–1.2
High-strength, low-alloy steels	0.9–1.2

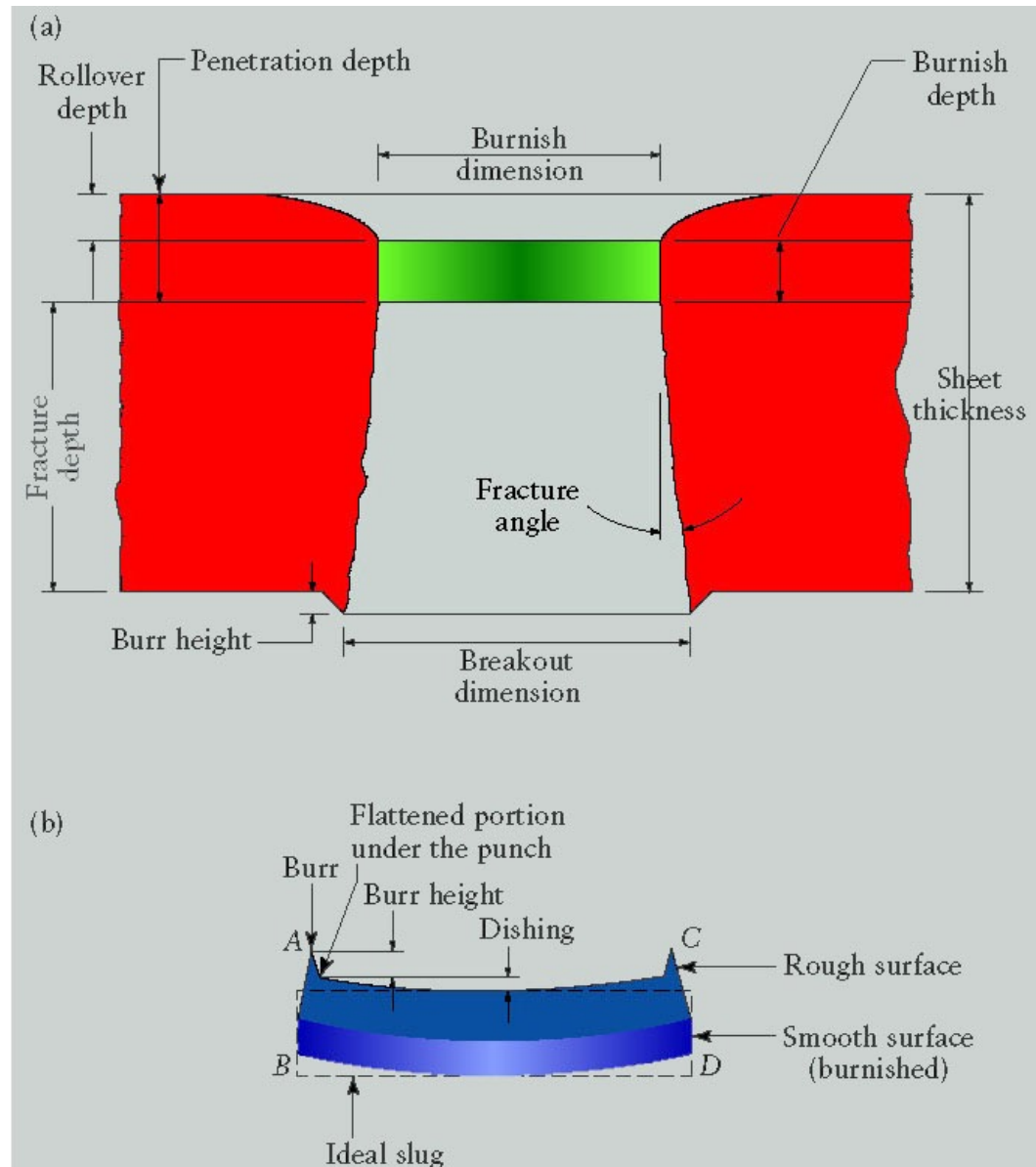
Sheet cutting

- Rectangular blanks created by shears, saws, rotary cutters
- These blanks can
 - be further sheared into more complex shapes
 - be further formed (bent, deep drawn, etc) into more complex shapes
 - also be the final product
- Shearing starts with cracks developed on the top and bottom by exceptionally high shear stresses
 - **A fracture process**
- The *punch* is typically the moving part
- The *die* is the stationary part

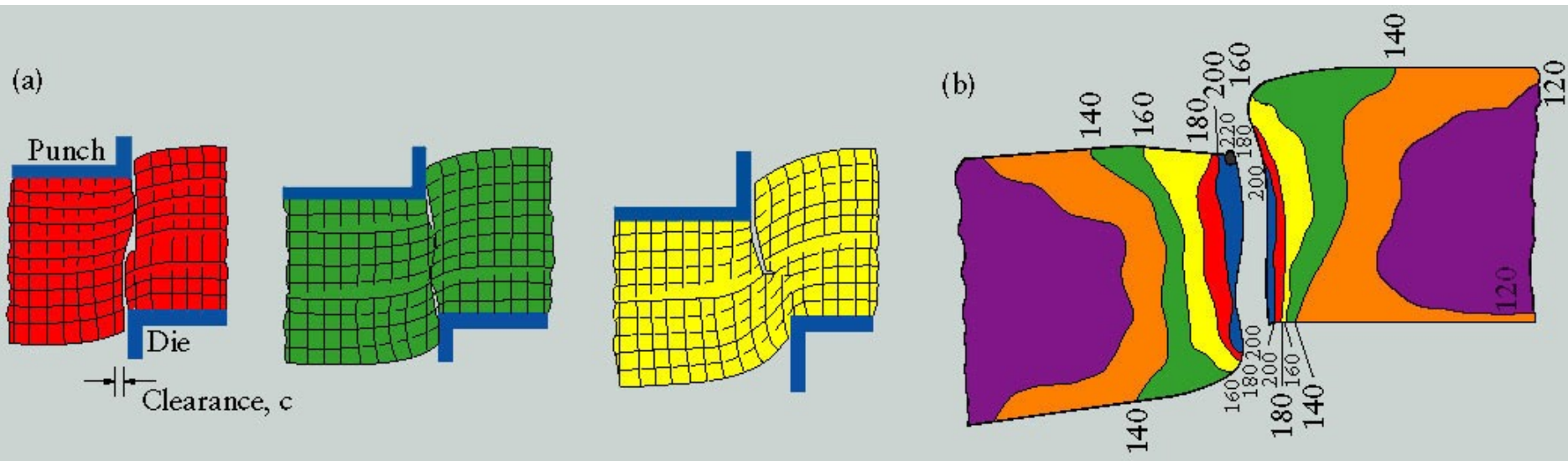


Basics of the sheet cutting

- Typically rough fracture surfaces are created
- Smoothing of this surface occurs by rubbing on the shear blades or the die

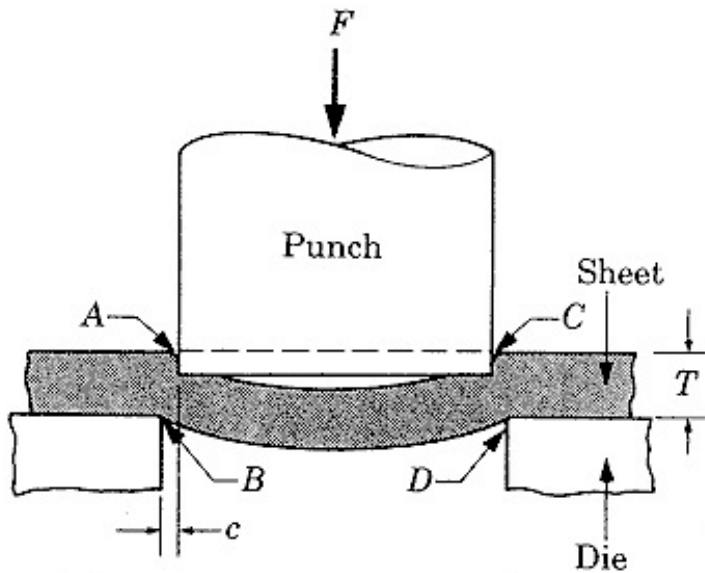
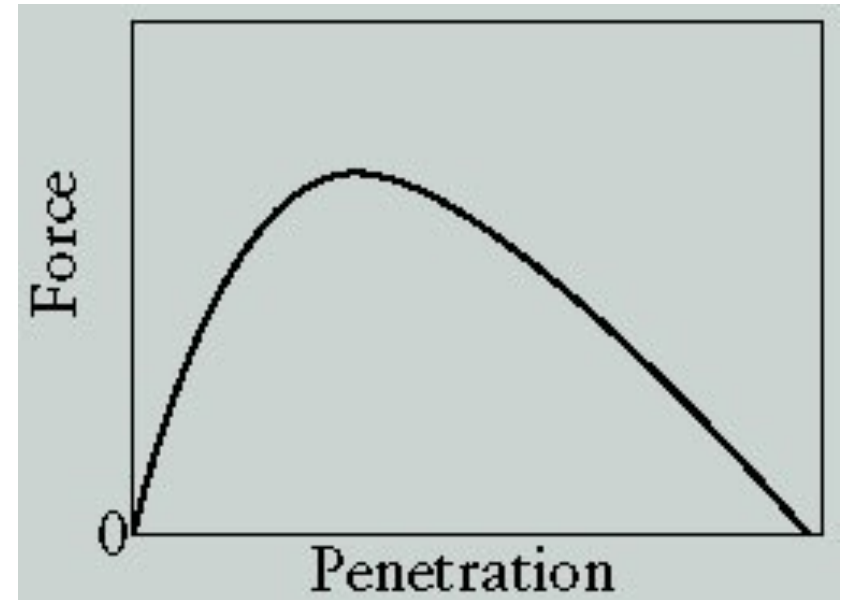


Clearance effect



(a) Effect of clearance c between the punch and die on the deformation zone in shearing. As clearance increases, the material tends to be pulled into the die, rather than being sheared. In practice, **clearances usually range between 2% and 10% of the thickness of the sheet.** (b) Microhardness (HV) contours for a 6.4-mm-thick (0.25-in.-thick) AISI 1020 hot-rolled steel in the sheared region.

Maximum process force



$$F_{\max} = 0.7 t L (\text{UTS})$$

where

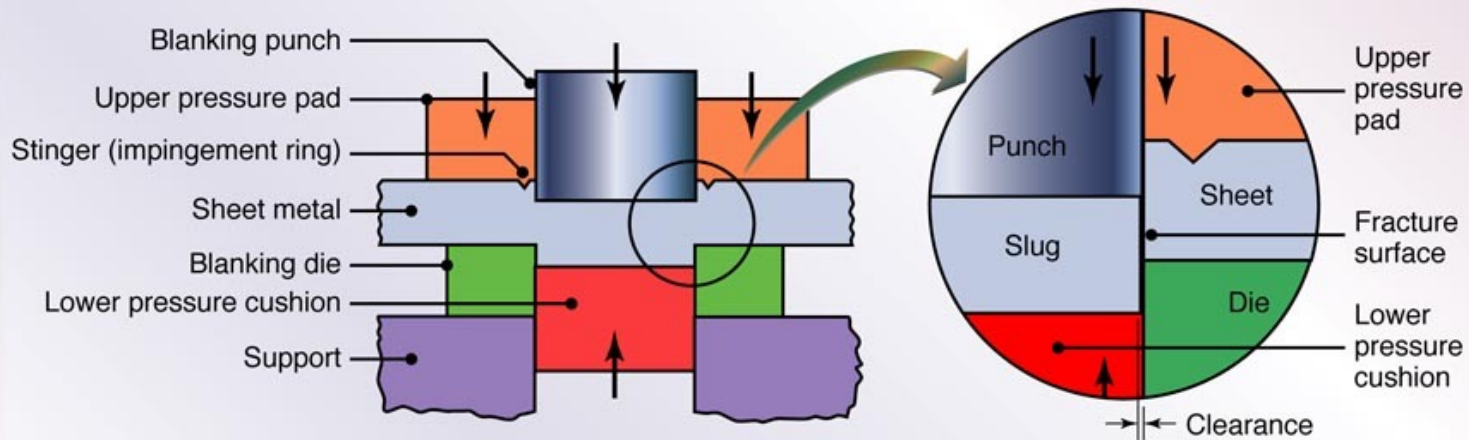
- | | |
|-----|---|
| F | force |
| t | workpiece thickness |
| L | total sheared length (the circumference in this case) |
| UTS | Ultimate tensile strength of the workpiece material |

Fine blanking

12



(a)



(b)

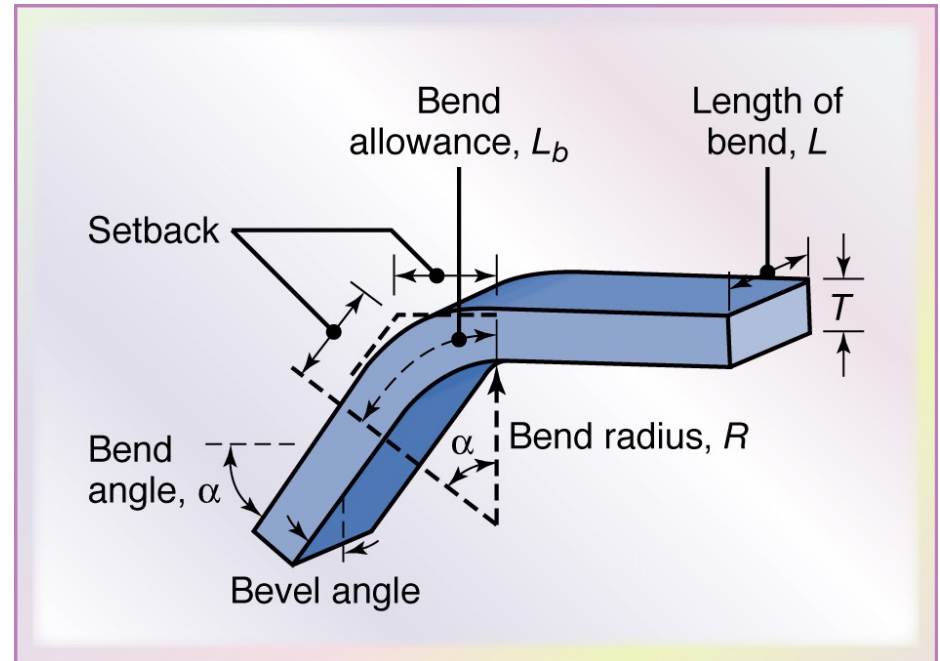
Bending

- **Advantages**

- Easy to perform
- Simple, low cost tooling
- Fairly precise

- **Disadvantages**

- Limited in the shapes it can produce
- Spring back difficult to estimate
- Some materials difficult to bend without tearing or necking



Bend Allowance: length of the neutral axis in the bend area

NB: length of bend=width of the sheet

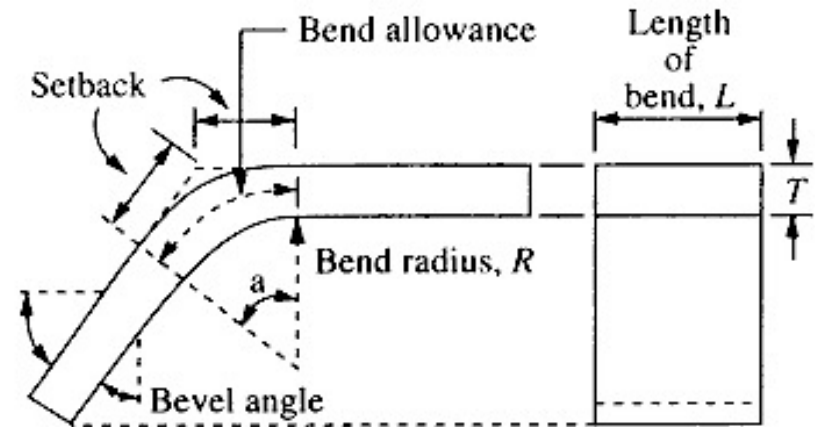
Process mechanics

- Bend allowance**

$$L = \alpha (R + kT)$$

where

- α is bend angle in radians
- L is the bend allowance
- R is bend radius
- T is thickness
- k is constant (ranges from 0.33 { $R < 2T$ } to 0.5 { $R > 2T$ })



- Neutral Axis**

- Is located where the engineering strain is zero
- If it is at the center of the sheet, $k = 1/2$ and
- Bend allowance = $\alpha(R + T/2)$

- Engineering strain**

$$e_o = e_i = \frac{1}{(2R/T) + 1} \quad \longrightarrow \quad \frac{R}{t} \downarrow \downarrow \quad e_o \uparrow \uparrow$$

Minimum bend radius

- As the material is bent, the tensile strain at the outer fibers increases until they crack
- The bend conditions for failure are best described by the *bend radius* at which cracking occurs
- The **Minimum Bend Radius (MBR)** is defined to occur when a crack appears at the outer fibers
- The terminology is to describe this condition in terms of the thickness of the material
I.E.> the MBR is 1T, 2T, 5T, 10T etc

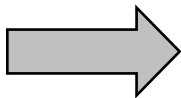
Minimum bend radius

- The true strain at cracking on the outer fibers is equal to the strain at fracture of the sheet metal
- Hypotheses: the material is homogeneous and isotropic; the sheet is bent in a state of *plane stress*

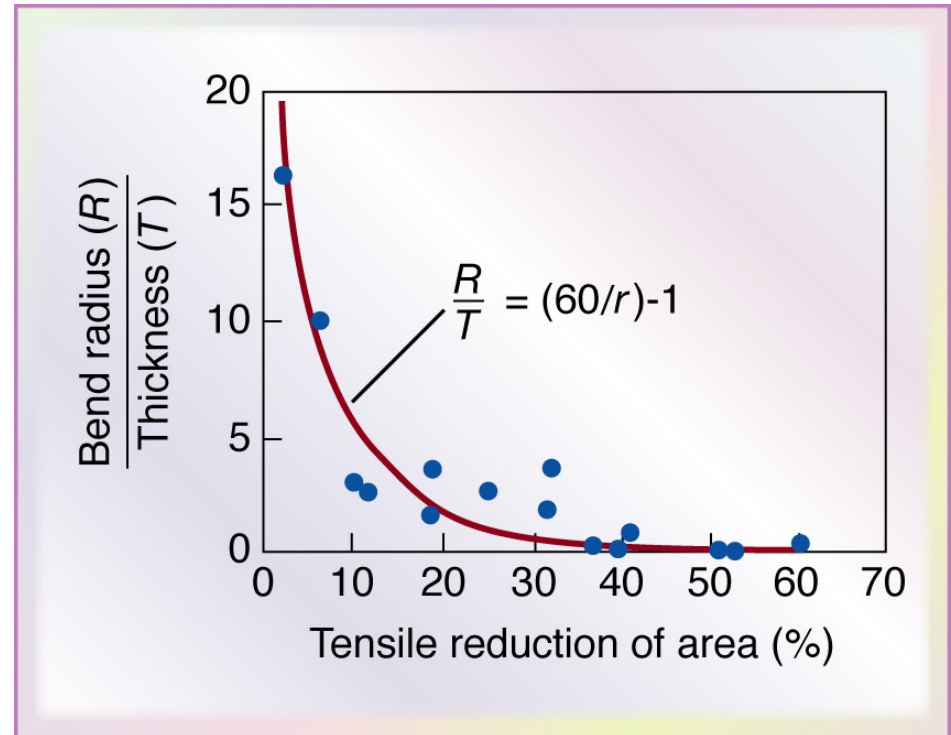
$$\varepsilon_f = \ln\left(\frac{A_0}{A_f}\right) = \ln\left(\frac{100}{100 - r}\right)$$

where r = % reduction of area of the sheet in a tensile test

$$\varepsilon_o = \ln(1 + e_o) = \ln\left(1 + \frac{1}{(2R/T) + 1}\right) = \ln\left(\frac{R + T}{R + (T/2)}\right)$$



Minimum $(R/T) = (50/r) - 1$



Minimum bend radius

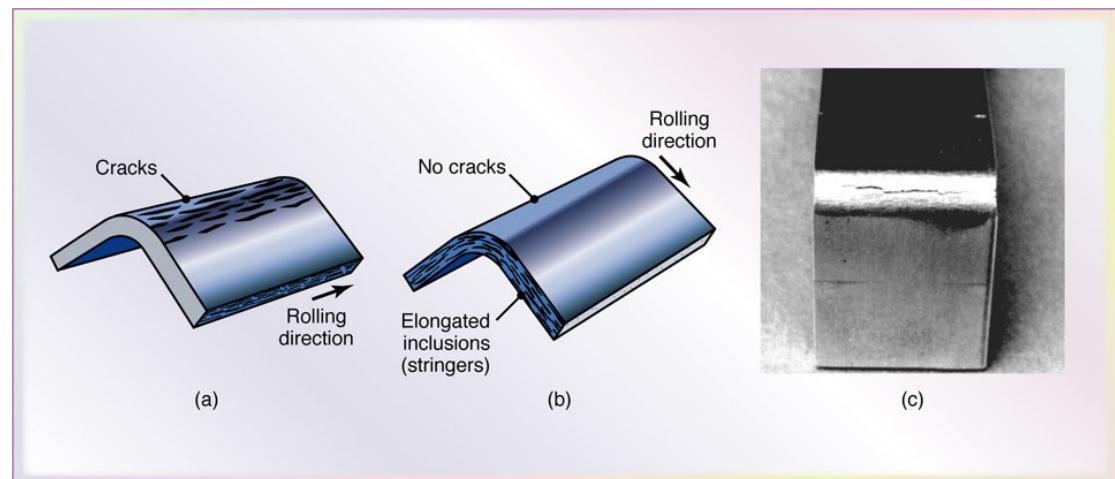
TABLE 16.3

Minimum Bend Radius for Various Materials at Room Temperature

Material	Condition	
	Soft	Hard
Aluminum alloys	0	$6T$
Beryllium copper	0	$4T$
Brass (low-leaded)	0	$2T$
Magnesium	$5T$	$13T$
Steels		
Austenitic stainless	$0.5T$	$6T$
Low-carbon, low-alloy, and HSLA	$0.5T$	$4T$
Titanium	$0.7T$	$3T$
Titanium alloys	$2.6T$	$4T$

Bendability

- It can be increased through heating or by application of hydrostatic pressure
- It depends on:
 - **Edge condition of sheet**
 - **Rough edges decrease bendability**
 - **Amount and shape of inclusions**
 - **Stringers more detrimental than globular shaped inclusions**
 - **Amount of cold work on edges due to shearing**
 - **Anisotropy**
 - **Elastic modulus - the springback phenomenon**



Springback

It is caused by the elastic behavior of workpiece material – elastic recovery

The final bend angle α_f is **smaller** and the final bending radius R_f is **larger**

$$\text{Bend Allowance} = \left(R_i + \frac{T}{2} \right) \alpha_i = \left(R_f + \frac{T}{2} \right) \alpha_f$$

where:

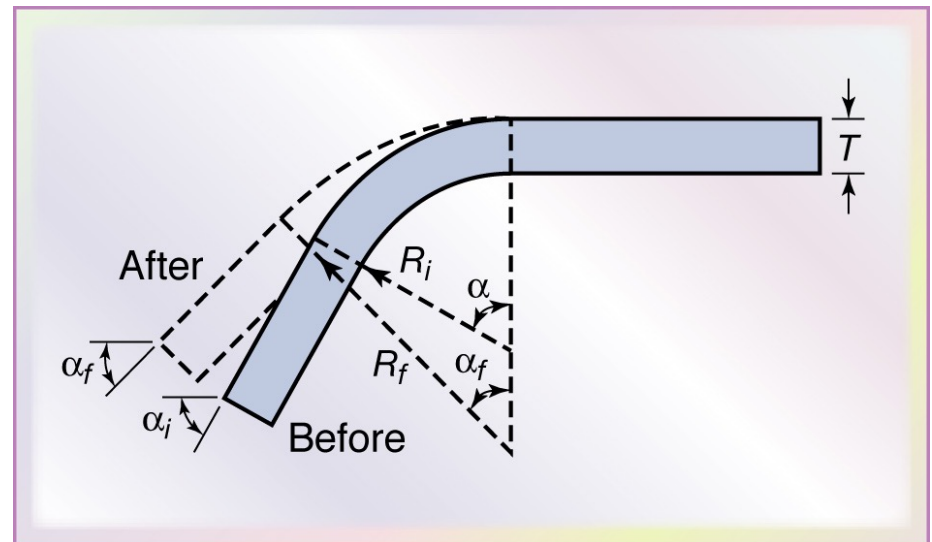
R_i is the required bend radius

R_f is the actual bend radius

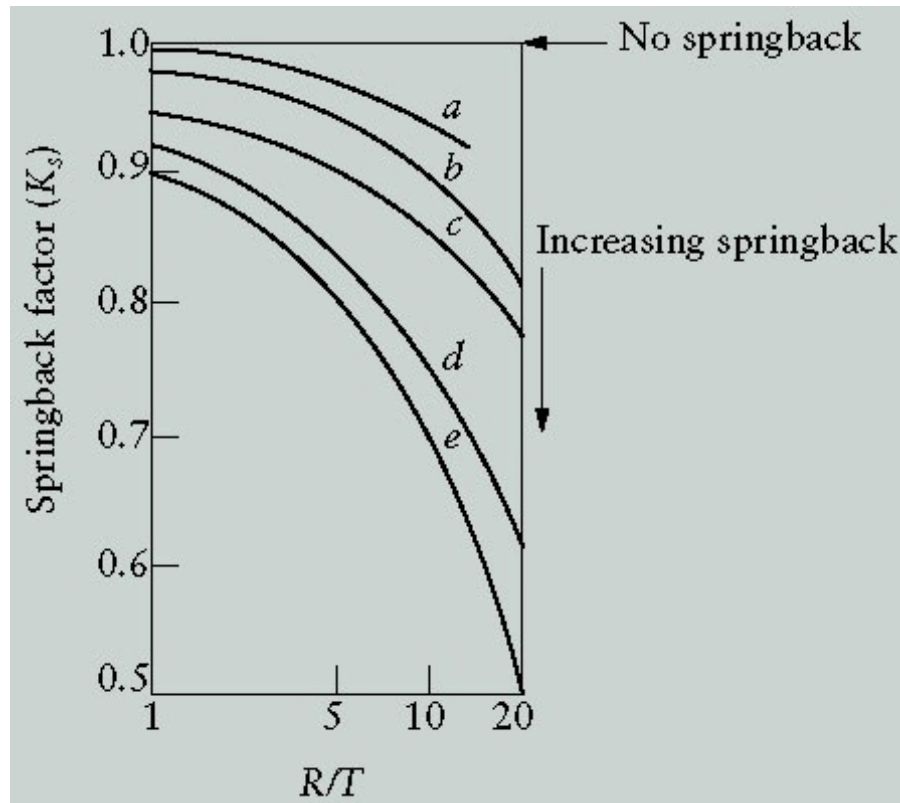
T is the thickness

Springback factor

$$K_s = \frac{\alpha_f}{\alpha_i} = \frac{\left(\frac{2R_i}{T} \right) + 1}{\left(\frac{2R_f}{T} \right) + 1}$$



Springback



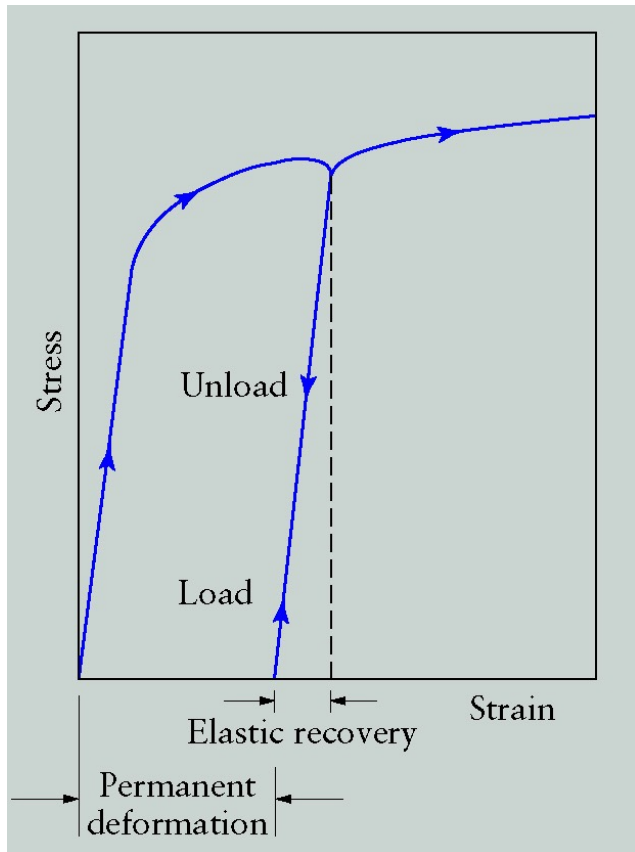
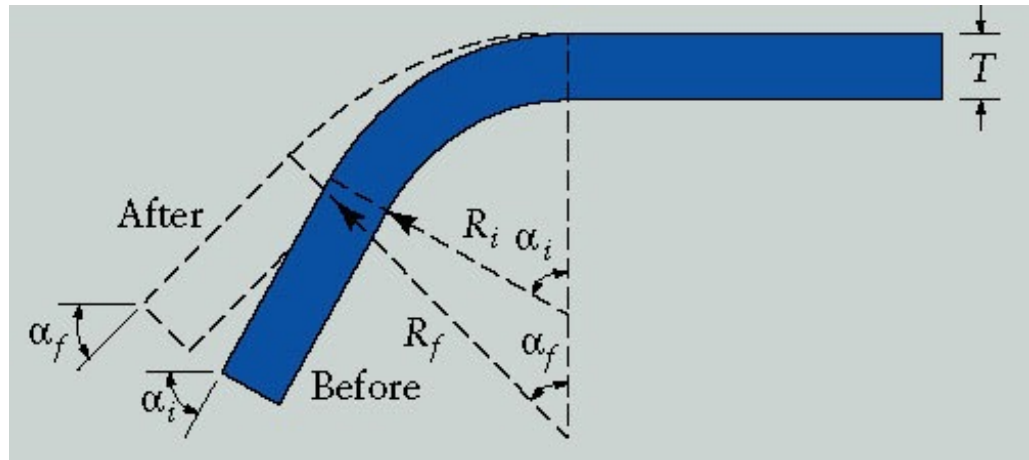
$$K_s = \frac{\alpha_f}{\alpha_i} = \frac{(2R_i / T) + 1}{(2R_f / T) + 1}$$

$K_s = 1$, no springback

$K_s = 0$, complete elastic recovery

Springback factor K , for various materials: (a) 2024-0 and 7075-0 aluminum; (b) austenitic stainless steels; (c) 2024-T aluminum; (d) 1/4- hard austenitic stainless steels; (e) 1/2-hard to full-hard austenitic stainless steels.

Springback



$$\frac{R_i}{R_f} = 4 \left(\frac{R_i Y}{ET} \right)^3 - 3 \left(\frac{R_i Y}{ET} \right) + 1$$

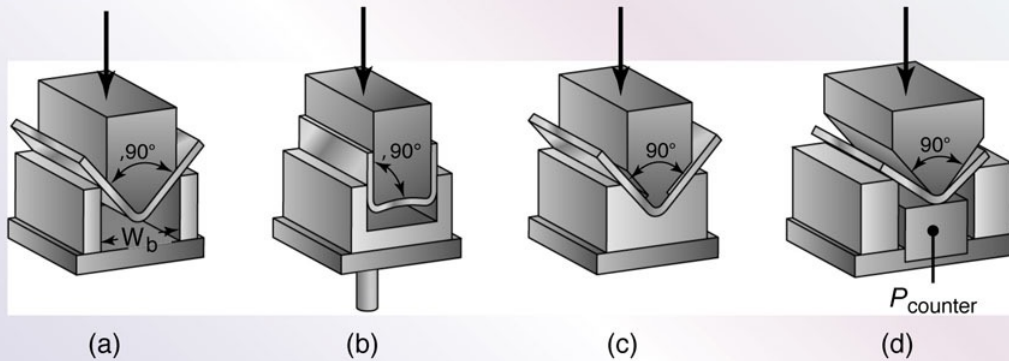
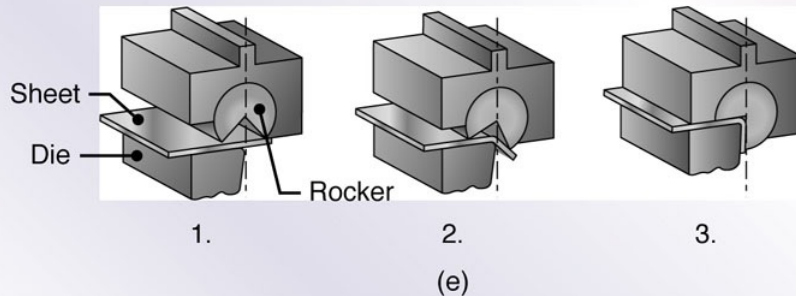
where

- R_i is the required bend radius
- R_f is the actual bend radius
- Y is the uniaxial yield stress
- E is the elastic modulus
- T is the thickness

Springback

It can be compensated by

- **Overbending**
- **Applying compressive stresses to the bend zone**
- **Stretch bending/forming**
- **Raising temperature**

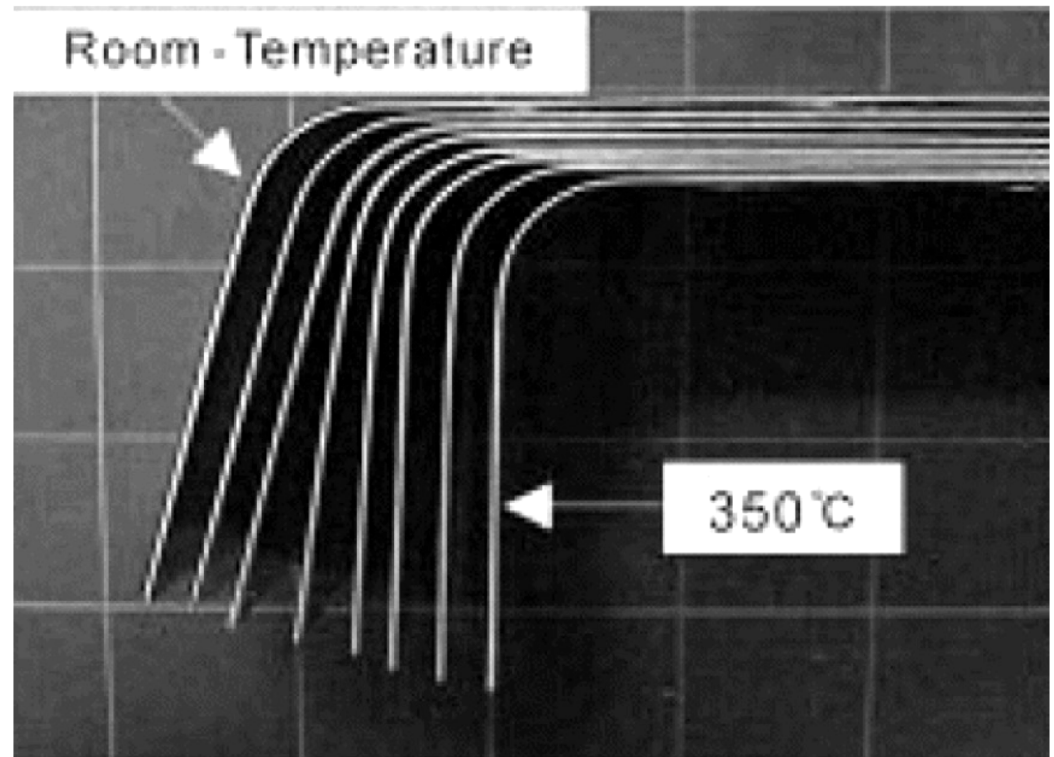


Temperature effect on springback

Reduction of material flow stress with temperature increase



Reduction of elastic recovery



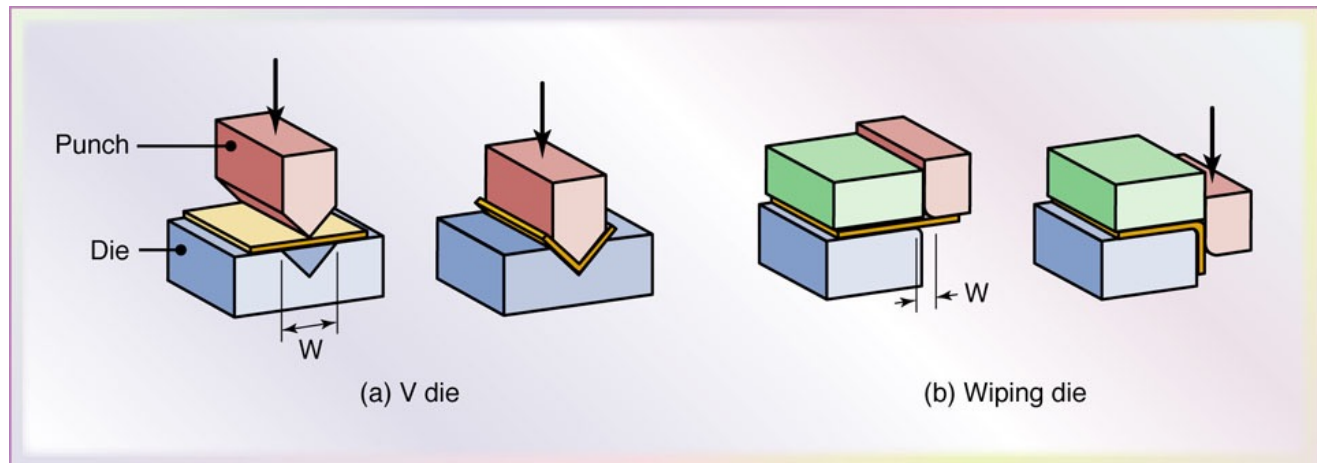
Elastic recovery at different temperatures. Material AA 5052

Process maximum force

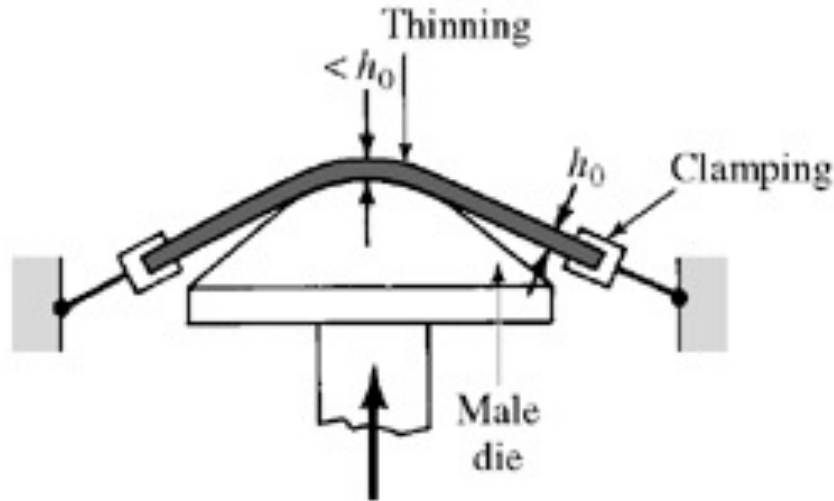
$$F_{\max} = (k \text{ UTS } L T^2)/W, \text{ excluding friction}$$

– Where

- UTS is the yield strength of the material
- L is the length of the bend
- T is the material thickness
- W is the width of the die opening
- k is a constant that depends on the die shape (k=1.2-1.33 for V-shaped dies)
- The bending force is also a function of punch travel; it increases from zero to a maximum

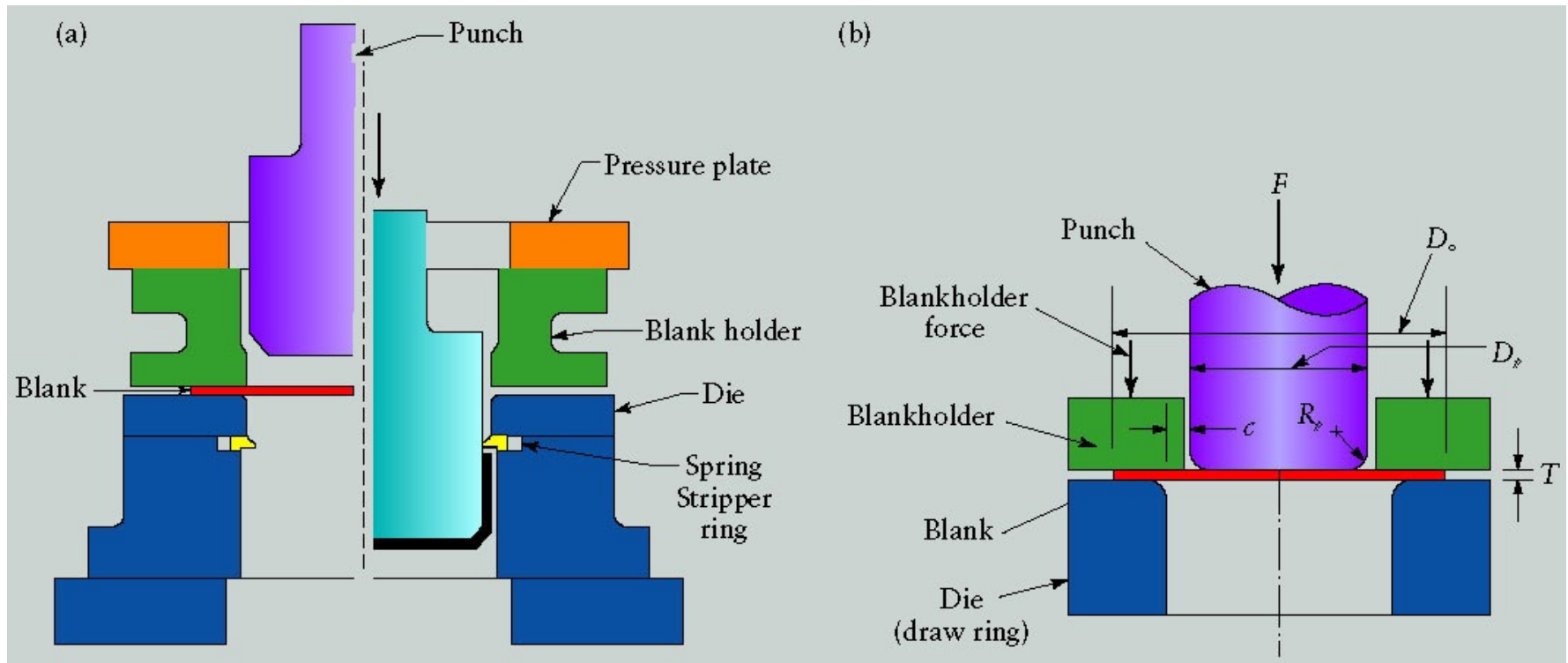


Stretching



- The sheet metal is clamped around its edges and stretched over a die or form block, which moves upward, downward, or sideways
- The shape is developed entirely at the expense of the sheet thickness
- To be controlled the amount of stretching to avoid tearing

Deep drawing



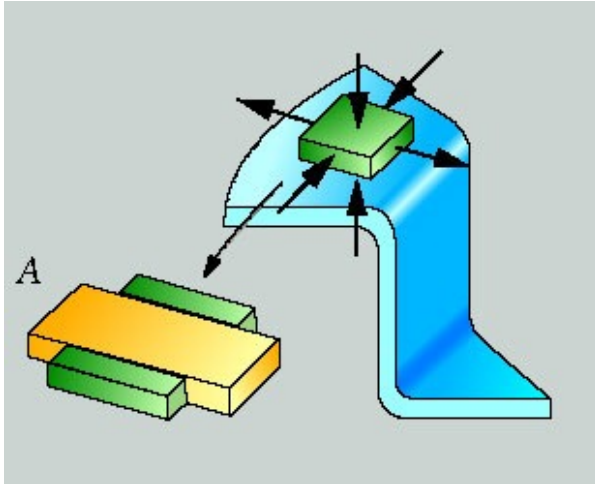
Advantages

- Very high production rates (e.g. cans)
- Can make parts no other process can make
- Containers of all shapes and sizes

Disadvantages

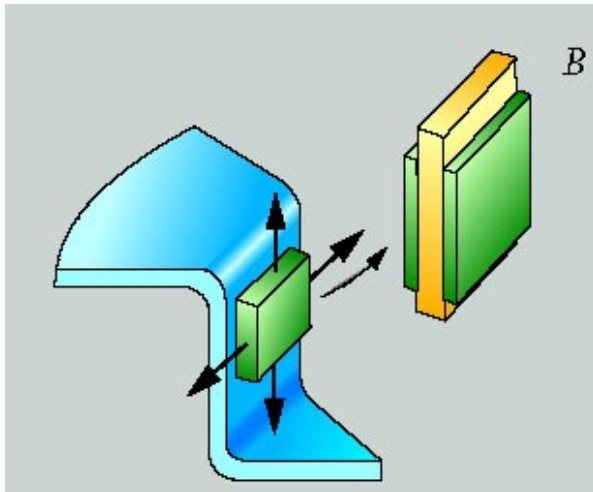
- Limited shapes
- Material quality critical to obtain high-quality parts
- Dies are expensive

States of stress



Under the blankholder (A position):

- Compressive through the thickness
- Tensile along the radius
- Compressive along the circumference due to decreasing blank circumference



In the die (B position):

- Mostly tensile in the punch direction
- Also tensile at right angles to the punch direction because of the cup contraction under tensile stresses in the cup wall
- Stresses cause material to thin in punch direction and shrink around the die in the circumferential direction

Deep drawing parameters

- Blankholder force
 - **Too high** - workpiece **tears**
 - **Too low** - cup gets **wrinkles**
- Radius/diameter of the punch
- Diameter of the blank
- Thickness of the blank
- Clearance between the punch and die
 - **Clearances usually 1.07 to 1.14 thickness**
 - **Too low** - blank pierced
- Friction/lubrication
- Radius of entry into the die
- Radius on end of the punch
 - **too small** - **cracking at corners**
 - **too large** - **wrinkling**
- Punch force (dependent variable)

Process maximum force

Composed by the forces required to:

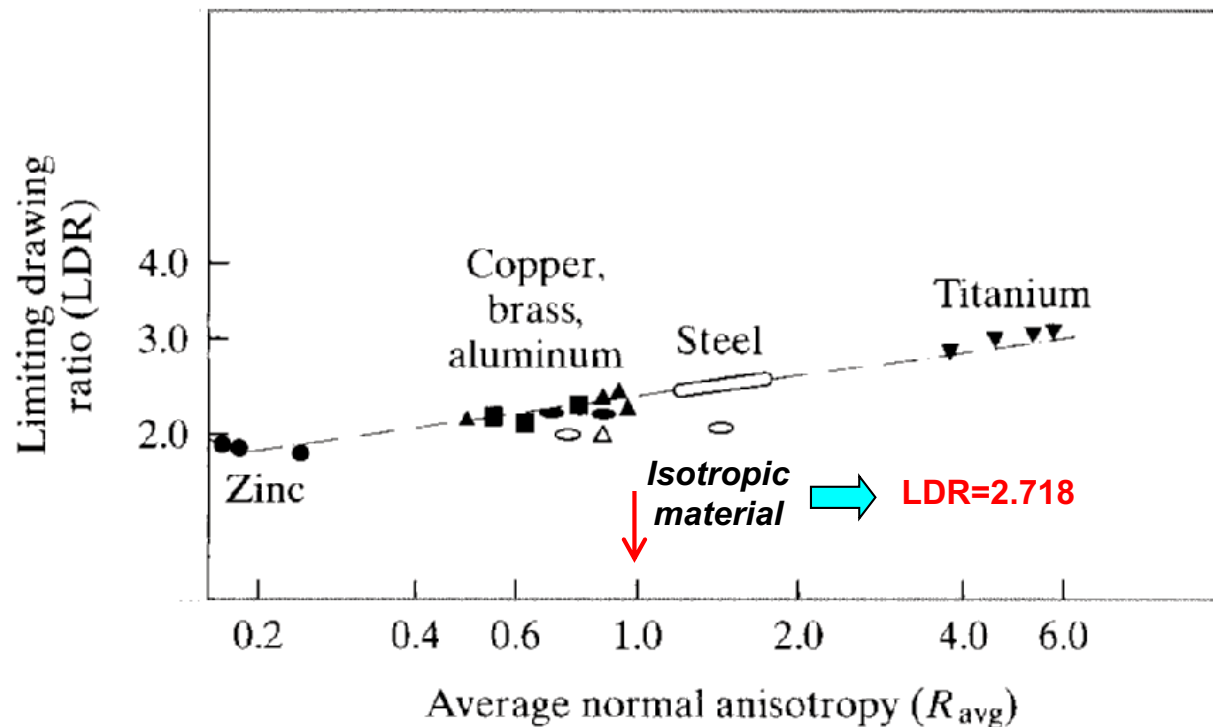
- compress the sheet in the flange circumferentially
- overcome friction between the blank and blankholder and die surfaces
- bend and unbend the sheet around the draw radii

$$F_{\max} = \pi D_p t_0 (UTS) \left(\frac{D_0}{D_p} - 0.7 \right)$$

Drawability

Limiting Drawing Ratio (LDR)

$$\text{LDR} = \max \frac{\text{Blank diameter}}{\text{Punch diameter}}$$



Planar anisotropy

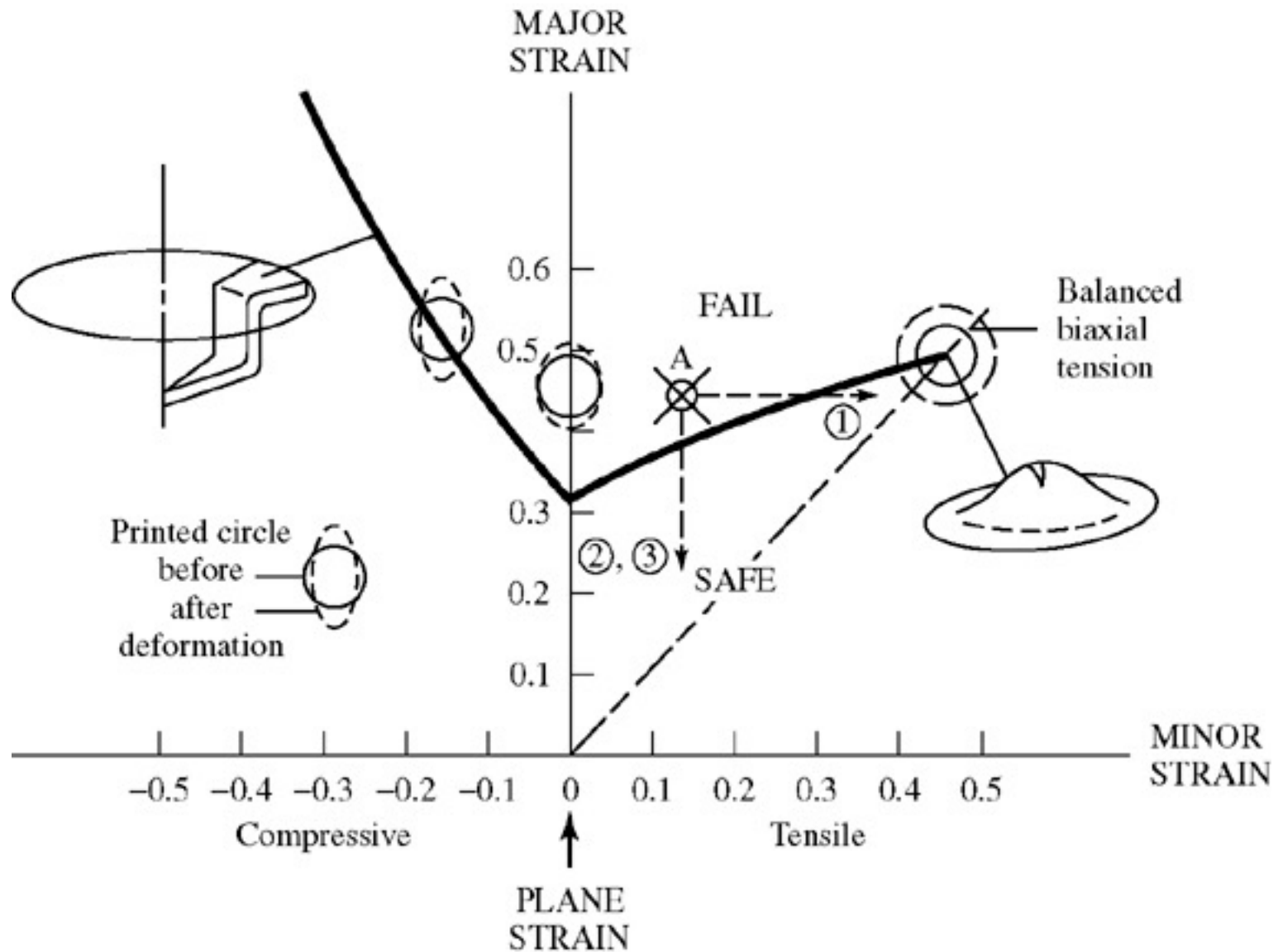
- If R_0 and R_{90} are different, the metal deforms differently in different directions of the drawing process
- This causes earing
 - **The top edge of the cup is no longer in one plane (wavy)**
 - **Ears must be trimmed off resulting in scrap**

$$\Delta R = (R_0 - 2 R_{45} + R_{90})/2$$

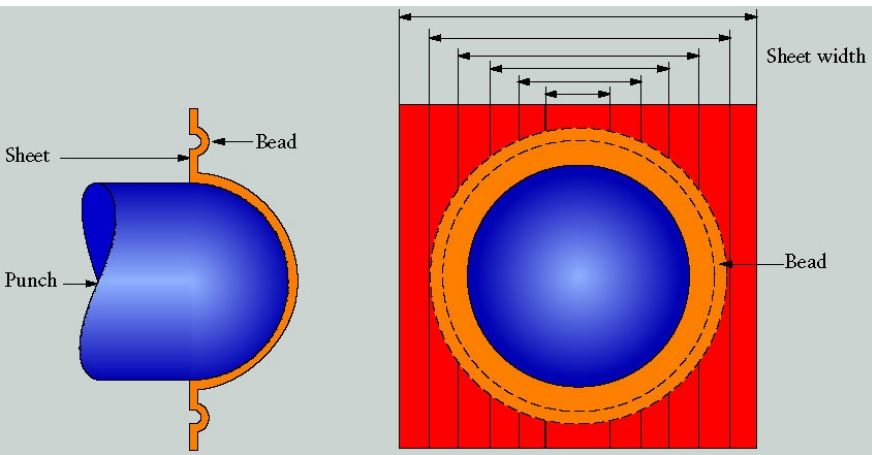
- Where R is the Normal Anisotropy and the subscripts are the direction in which R is measured relative to the rolling direction
- “Ears” are formed when ΔR is not zero



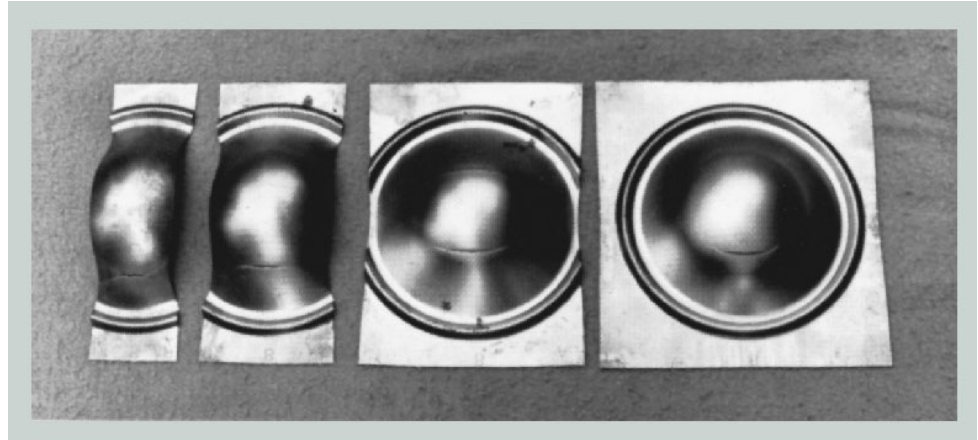
Forming limit diagram FLD



Nakajima test

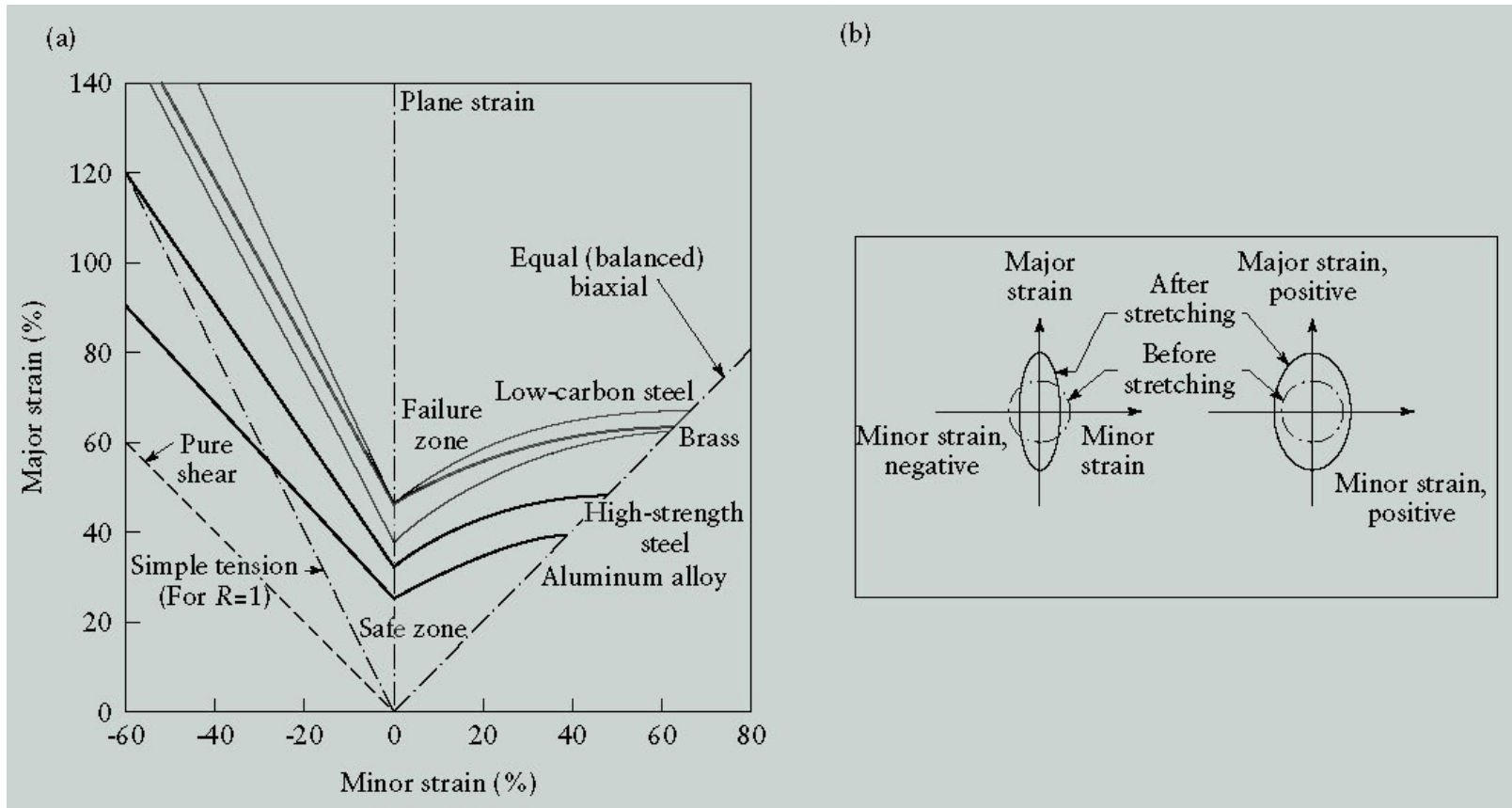


(a) Schematic illustration of the punch-stretch test on sheet specimens with different widths, clamped at the edges. The narrower the specimen, the more uniaxial is the stretching. (b) A large square specimen stretches biaxially under the hemispherical punch.



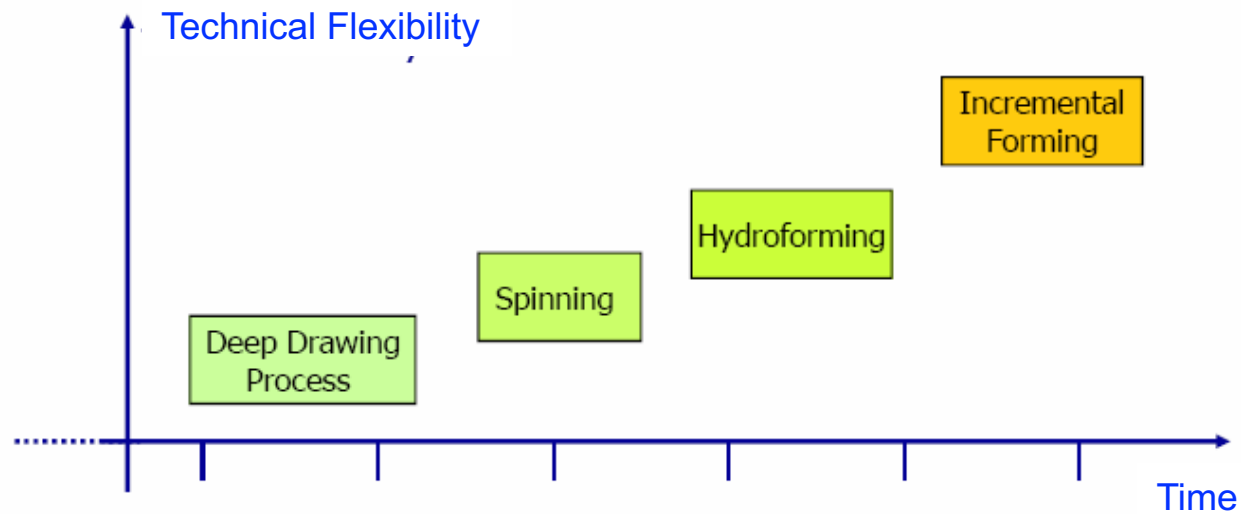
Bulge tests results on steel sheets of various widths. The first specimen (farthest left) stretched farther before cracking than the last specimen. From left to right, the state of stress changes from uniaxial to biaxial stretching.

Forming limit diagram FLD

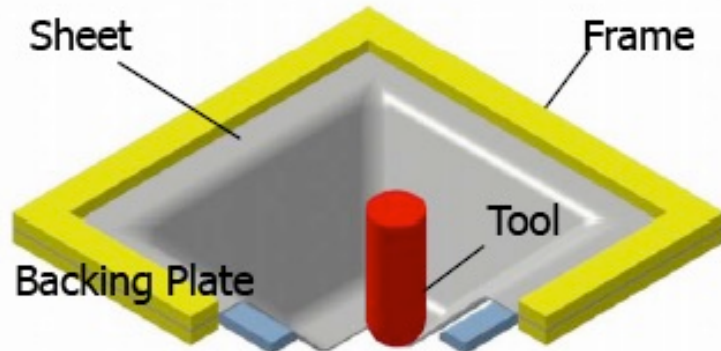
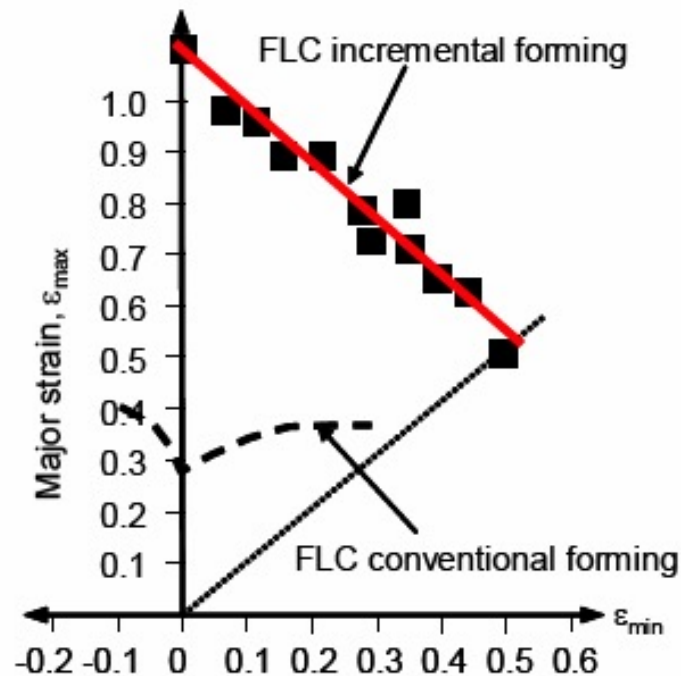
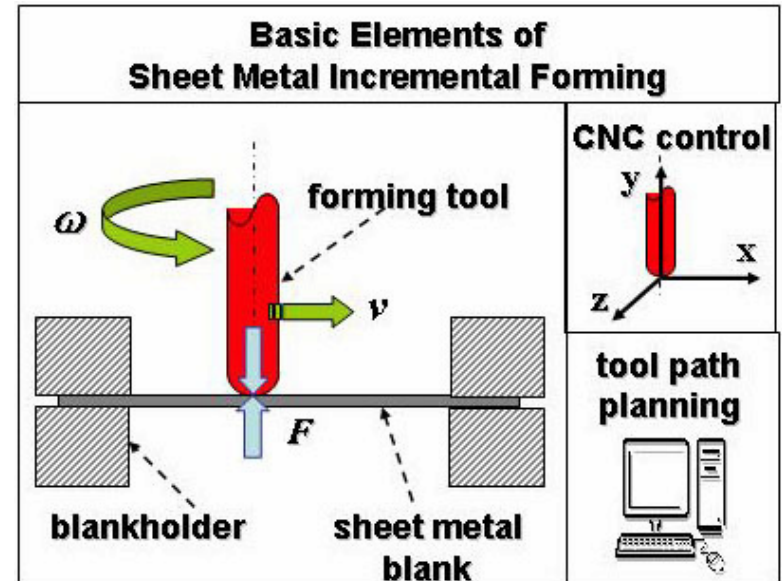
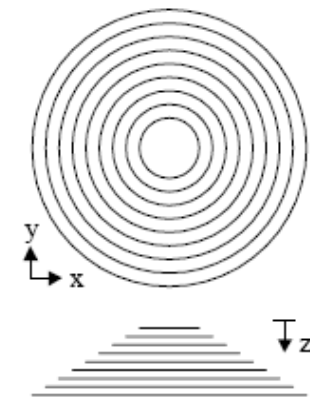


(a) Forming-limit diagram (FLD) for various sheet metals. The major strain is always positive. The region above the curves is the failure zone; hence, the state of strain in forming must be such that it falls below the curve for a particular material; R is the normal anisotropy. (b) Note the definition of positive and negative minor strains. **If the area of the deformed circle is larger than the area of the original circle, the sheet is thinner than the original, because the volume remains constant during plastic deformation.**

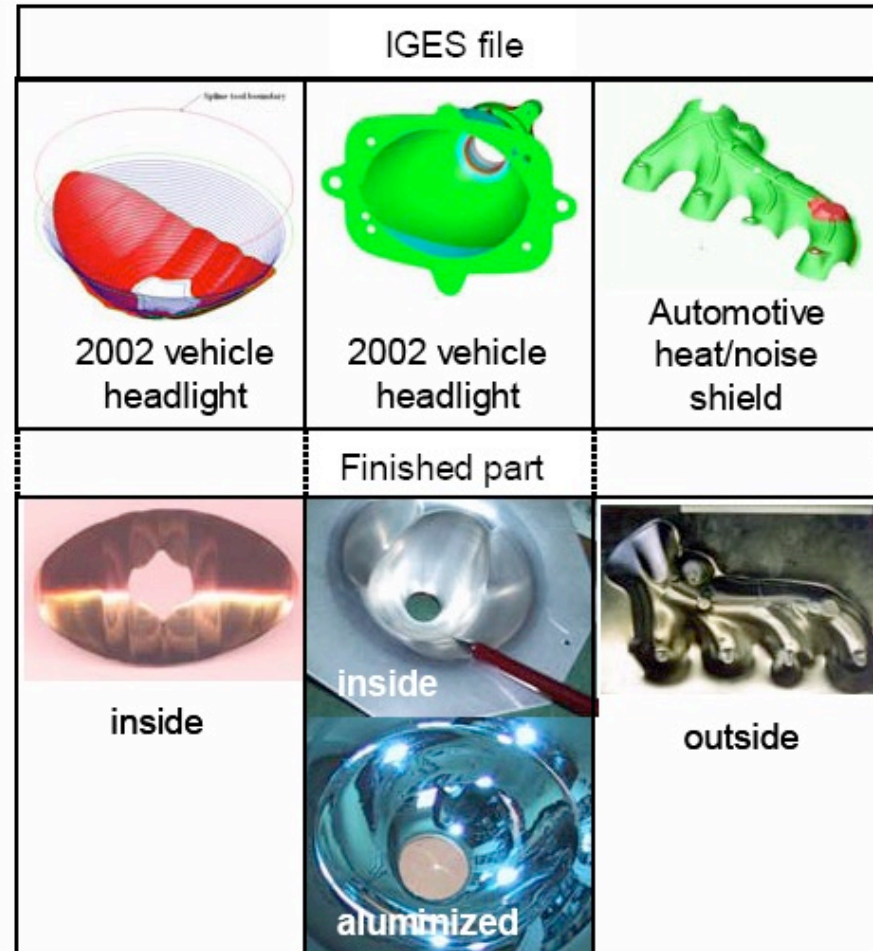
- ➡ Nuovi target richiesti dal mercato
- ➡ Volumi di produzione contenuti
- ➡ Continua innovazione di prodotto
- ➡ Necessità di attrezzature meno costose e di ridurre i tempi di set-up



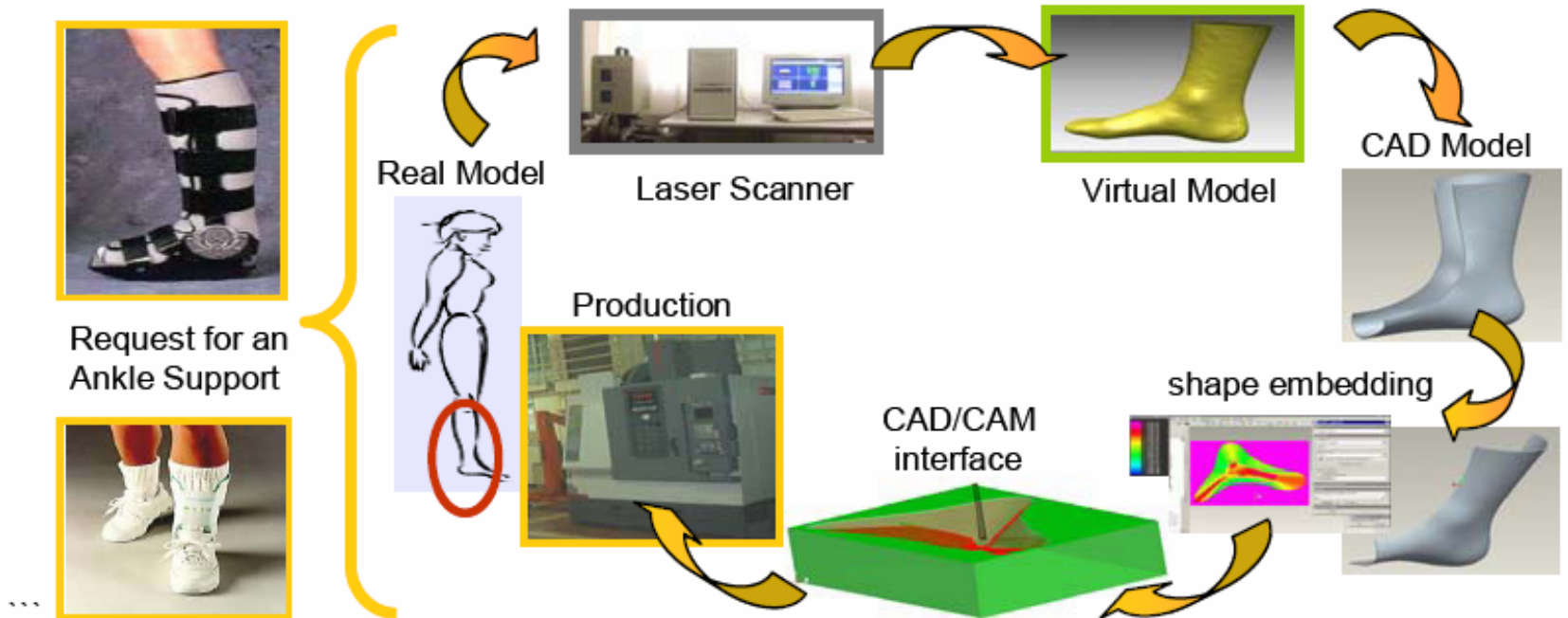
Incremental sheet forming



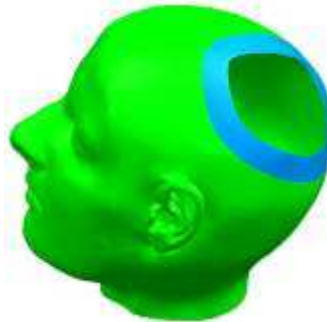
Examples



Example – ankle support

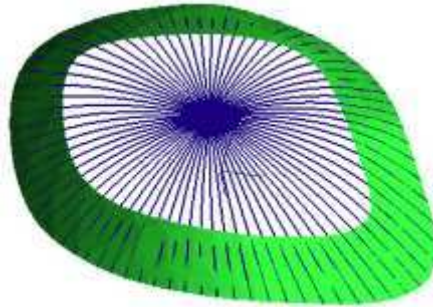
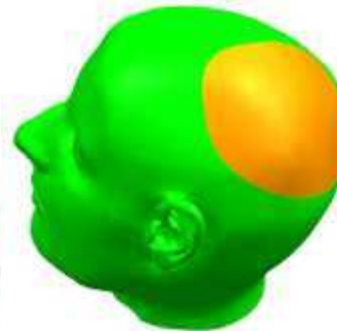
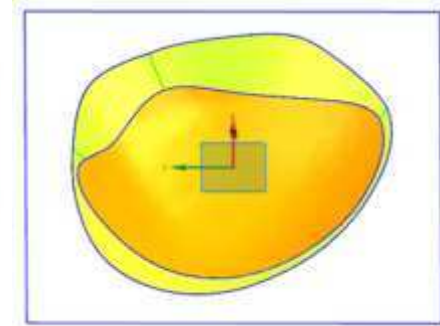


Example – cranial implant



Original model & identification of surrounding area

Generation of the incremental sheet forming tool path



Finished and trimmed part

