Lecture 4: Metals forming and cutting (‘Mise en forme des métaux’)

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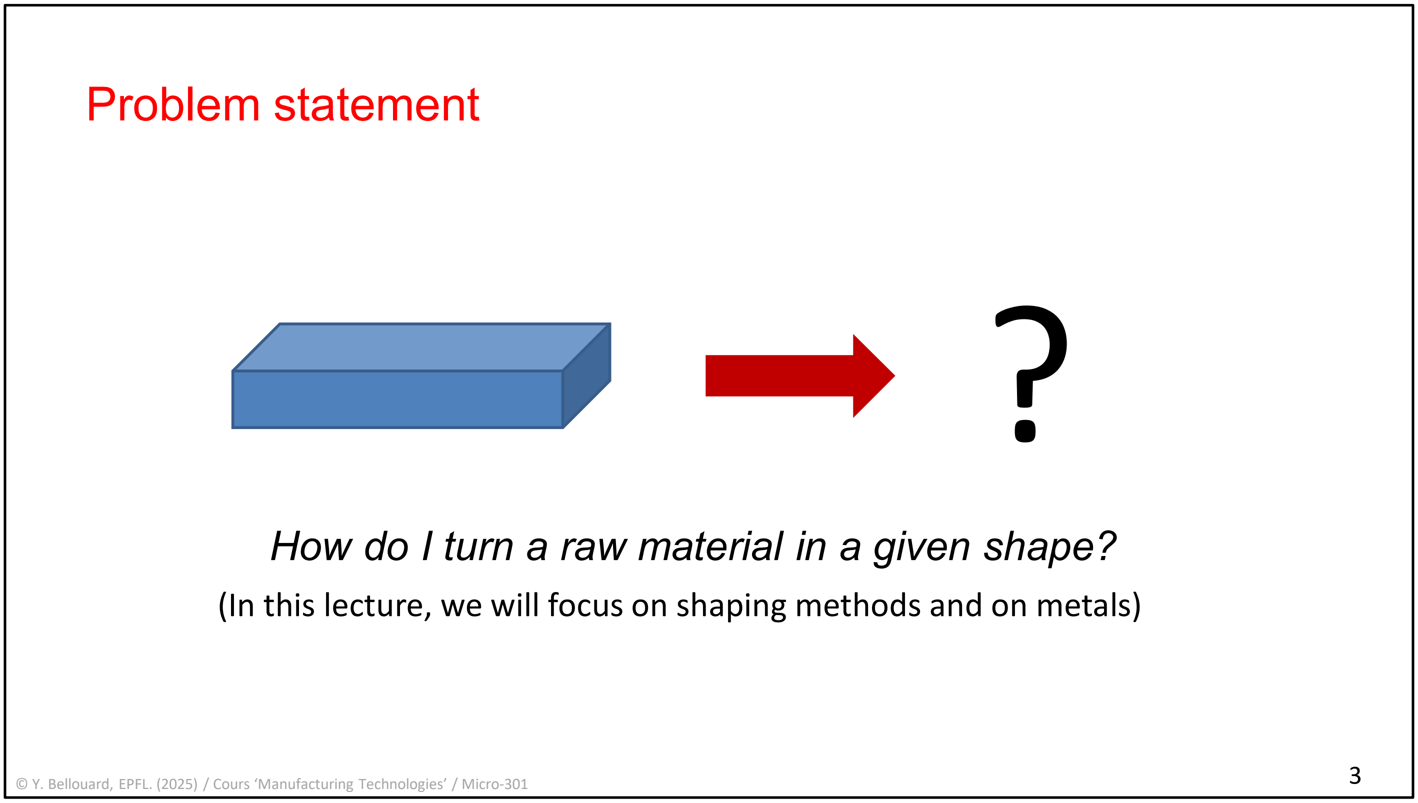
Today's lecture objectives

- Why metals?
- Forming of metals
- How materials deform?
- Mechanics of materials & microstructures
- Description of most common forming process

Metal forming is among the most used manufacturing process.

Many parts surrounding us make use of this process. It is therefore essential to be aware of it and of its basic working principles.

As we will discuss further on, metal forming is used across multiple scales, from large scale objects to tiny ones, like for the metal housing of a USB-C connector.



Problem statement

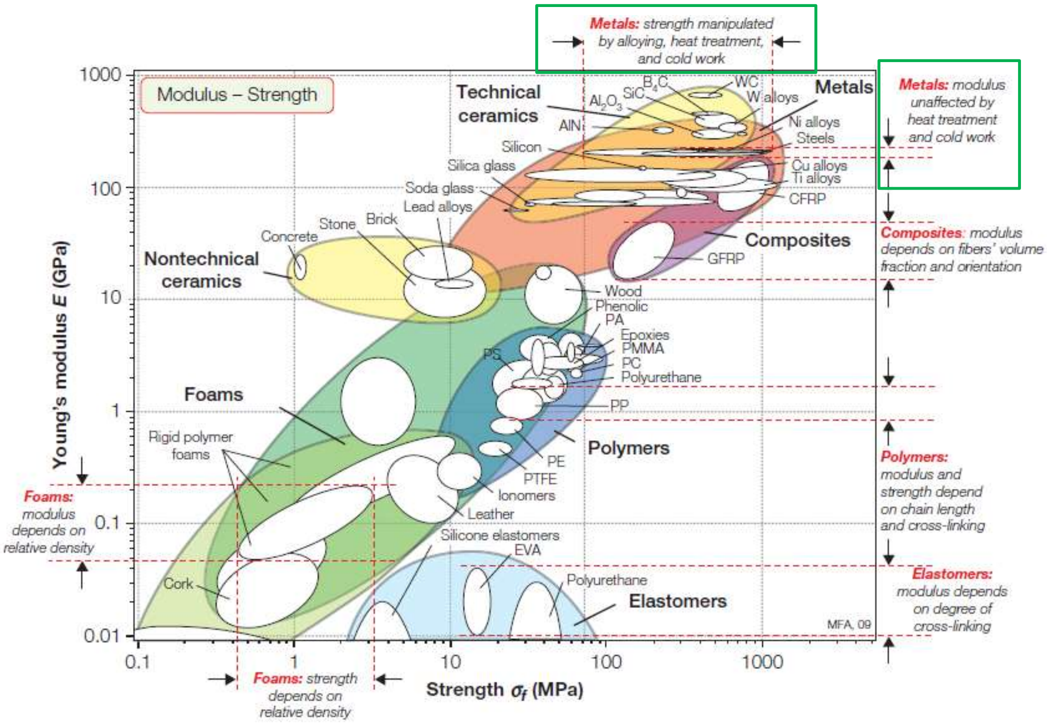
How do I turn a raw material in a given shape?

(In this lecture, we will focus on shaping methods and on metals)

The fundamental question at hands is: given a raw piece of material, for instance in the form of a strip or bar of metal, how can it be 'formed' into various arbitrary shapes?

Here, we will address specifically the topic of metal forming, but some variations of these methods may also be used (e.g., combined for instance with other process elements, such as heating or gas pressure) to other materials.

Hence, let us first start the discussion by highlighting the rationale for using metals as a raw materials for producing arbitrary shapes.

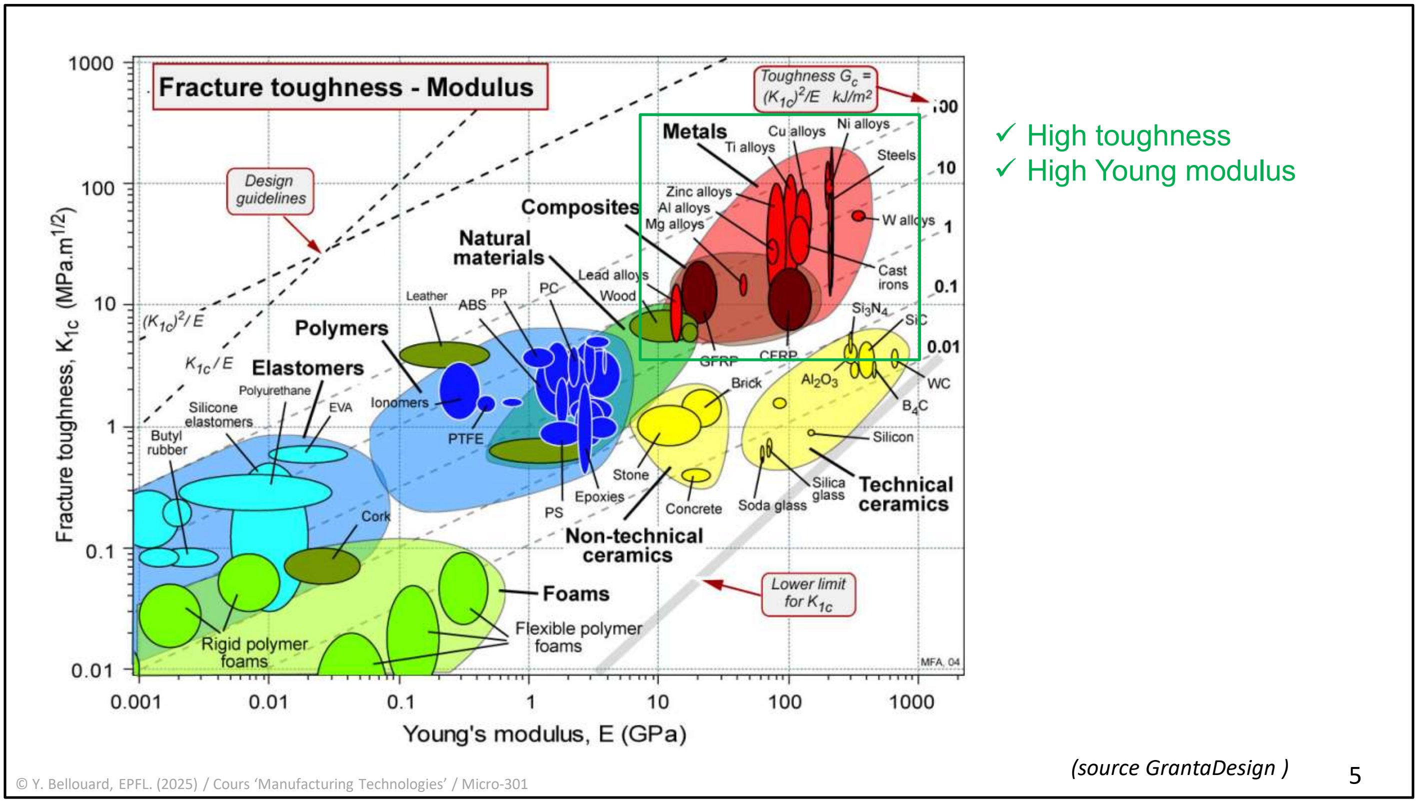


- ✓ High Strength (Elastic limit)
- ✓ High Young modulus

(Source M. Ashby, Materials selection in Mechanical Design, 4th edition, Elsevier)

In this global analysis, for analyzing key materials properties, it is useful once again to consider Ashby's plot representations.

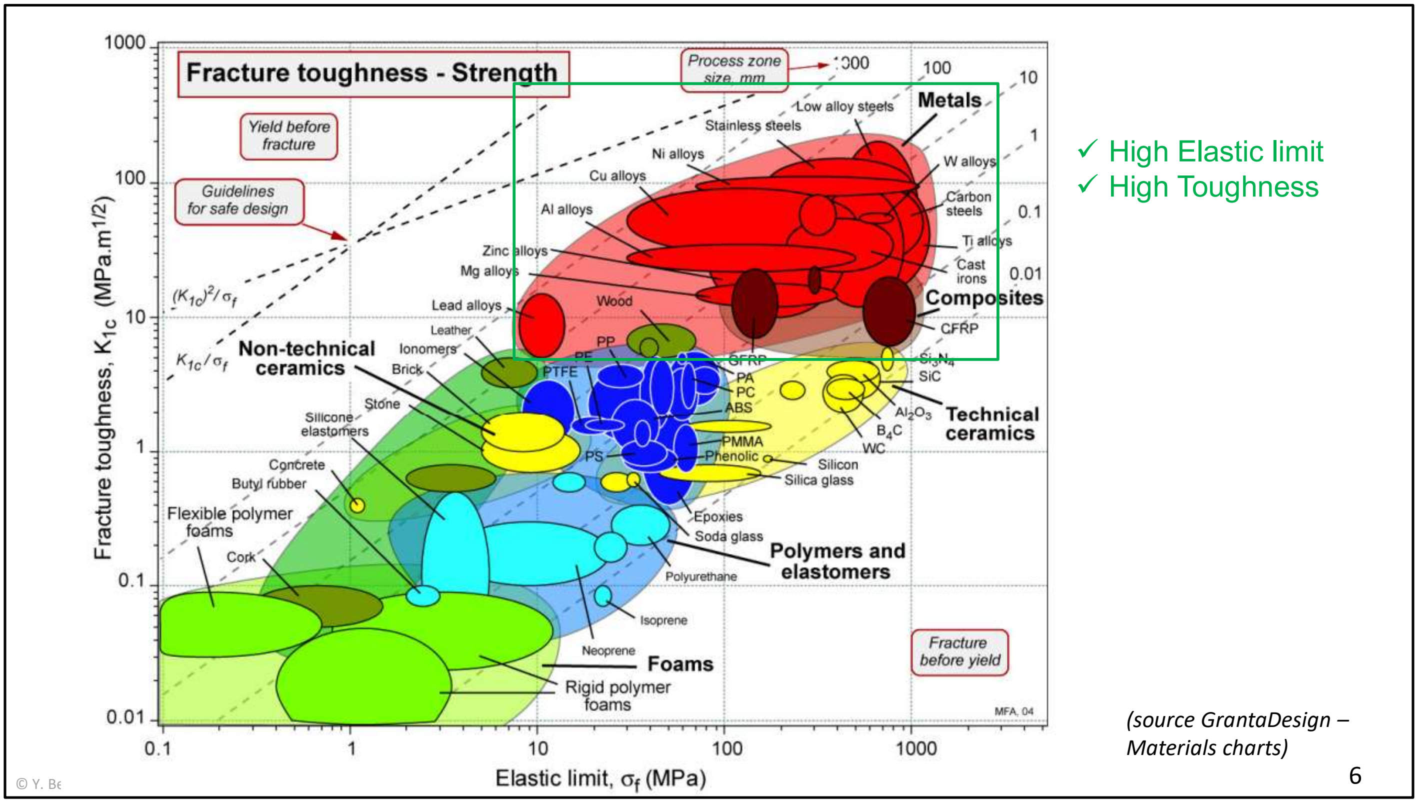
Looking at their mechanical properties, metals have among, both, the highest strength/elastic limit and Young's modulus.



- ✓ High toughness
- ✓ High Young modulus

(source GrantaDesign)

… but also, the highest toughness - which by definition describes 'the critical stress intensity factor of a sharp crack, where propagation of the crack suddenly becomes rapid' and propagates until rupture, in addition to among the highest Young's modulus.



✓ High Elastic limit
✓ High Toughness

(source GrantaDesign – Materials charts)

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A similar plot highlighting the high elastic limit and high fracture toughness of metals. As can be seen in this plot, clearly metals have unique position in the landscape of possible materials

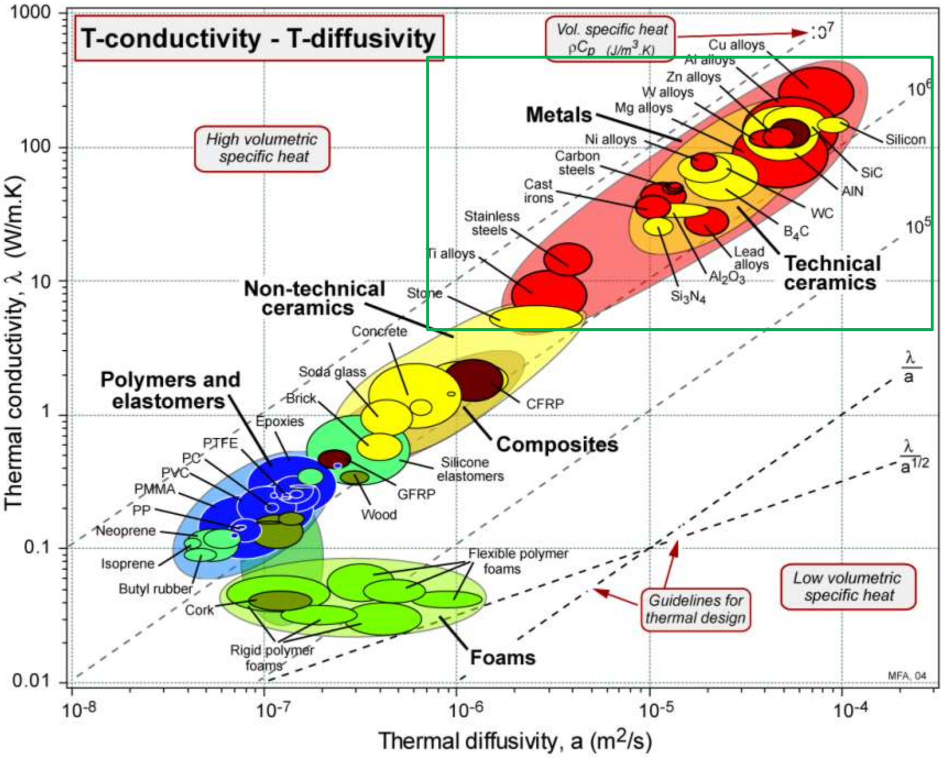
From a mechanical point of view...

- Metals have unique advantages among materials:
  - Among the highest Young's Modulus and ultimate strength
  - Their elastic limit can be engineered and tuned *without changing* the Young's modulus
  - Highest fracture toughen
  - Ductility

'Cold-work' / 'Strain hardening'
('Ecrouissage')

High manufacturability

Hence metals clearly have unique advantages among various family of materials, including having good **ductility** (i.e., 'the degree to which a material can sustain *plastic* deformation before failure'), an essential property in the context of putting materials into shapes, hence, governing the manufacturability of the material.



(source GrantaDesign – Materials charts)

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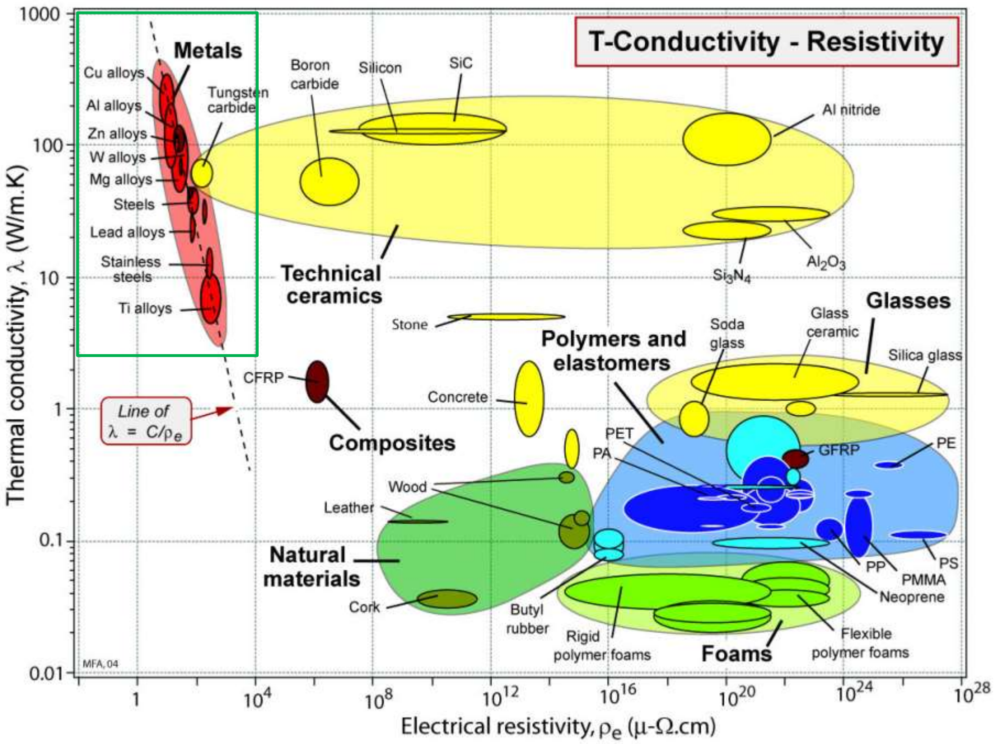
Metals also have useful thermal properties, such as a high **thermal diffusivity** (i.e., '*the rate at which heat transfer occurs through the material*') and high **thermal conductivity** (i.e., '*the ability to transfer heat through the material*').

Note that the two are related to one another, through the relation: $\alpha = \frac{\mathrm{k}}{\rho \mathrm{c}}$

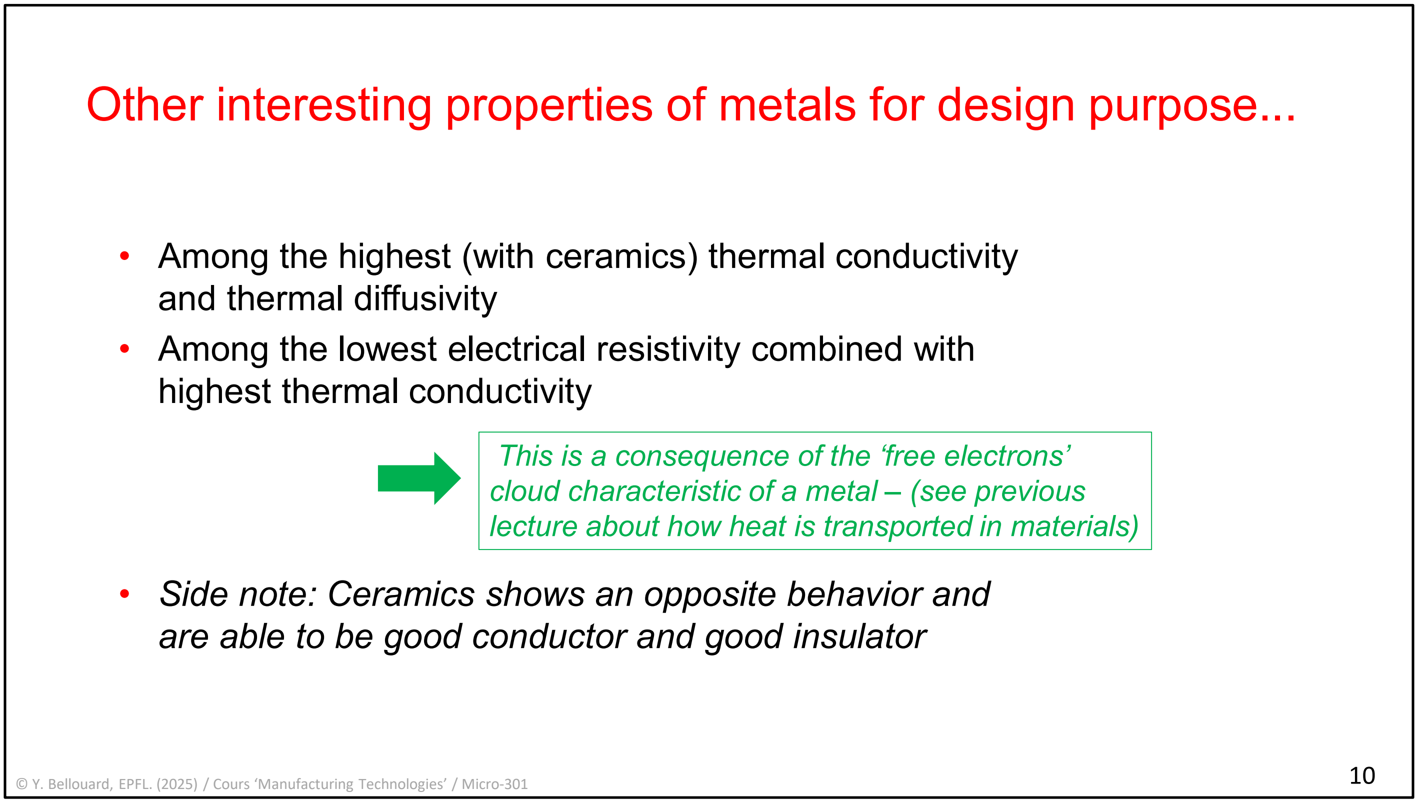
with α the thermal diffusivity, **k** the thermal conductivity, ρ the material density and **c**, the heat capacity.

There too, they share a 'leading position', together with ceramics.



(source GrantaDesign – Materials charts)

Finally, metals combine a *low* electrical resistivity with a *high* thermal conductivity. Note that there is a quasi linear relationship between thermal conductivity and resistivity.



Other interesting properties of metals for design purpose...

- Among the highest (with ceramics) thermal conductivity and thermal diffusivity
- Among the lowest electrical resistivity combined with highest thermal conductivity

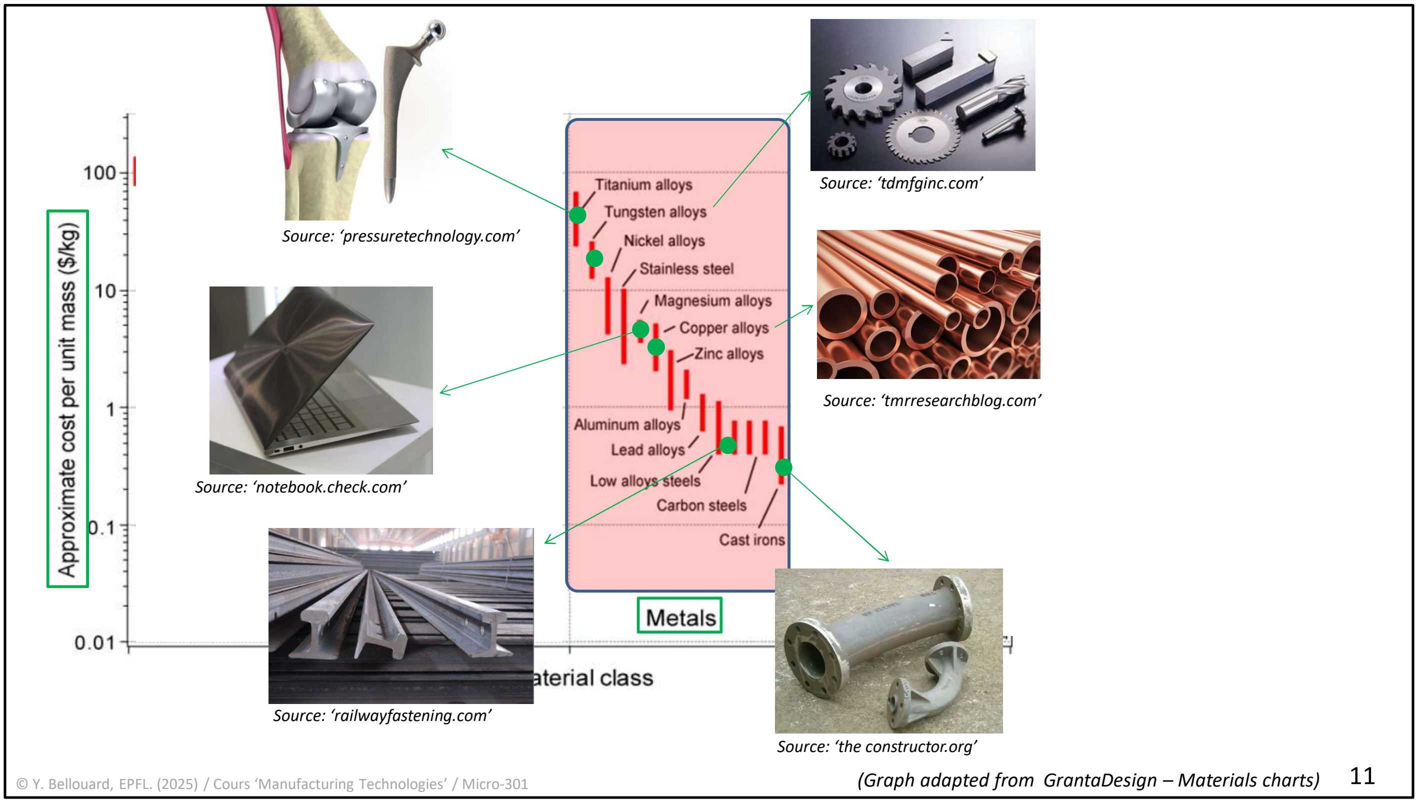
→ *This is a consequence of the 'free electrons' cloud characteristic of a metal – (see previous lecture about how heat is transported in materials)*

- *Side note: Ceramics shows an opposite behavior and are able to be good conductor and good insulator*

The list above summarizes key engineering properties of metals useful to be considered for designing purpose.

Note that the ability of metals to conduct electricity and heat well stems from their electronic structures, *i.e.,* the presence of a 'cloud of electrons' not bond to specific atoms as heat conduction is enhanced by the electron mobility.

One should not conclude too hastily that a good heat conductor is *intrinsically* a good electrical conductors. While it is in general true, counter-examples to this exist. Indeed, some ceramics can display excellent thermal conductivity but yet, poor electrical conductivity (see Ashby's plot in previous pages).



Source: 'pressuretechnology.com'

Source: 'tdmfginc.com'

Source: 'notebook.check.com'

Source: 'tmrresearchblog.com'

Source: 'railwayfastening.com'

Source: 'the constructor.org'

(Graph adapted from GrantaDesign – Materials charts)

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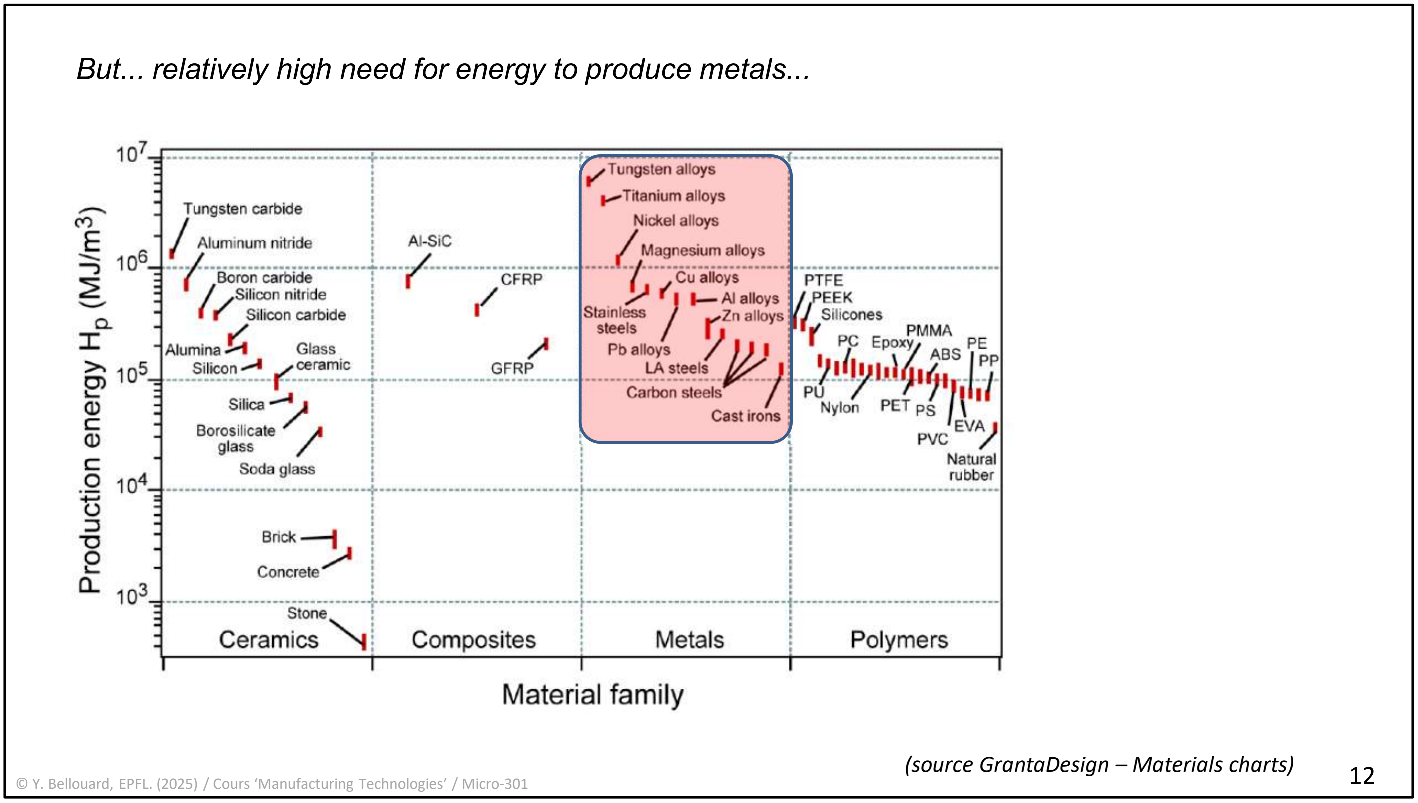
Finally, it is interesting to compare the cost between most common metals and their typical applications.

From the cheapest to the most expensive:

- Cast irons ('ferraille') are low-cost metals, often used for structural parts that do not require extreme performances, but however, a high volume of materials.
- Carbon steels are typically used for large parts, such as rails.
- Copper alloys (which prices can be non negligible) for their superior heat and electrical conductivities (with yet relatively poor mechanical performances).
- Magnesium alloys are typically favored for lightweight structures yet providing sufficient strength. Typically use are for consumer products, such laptops.
- Tungsten alloys (such as tungsten carbide) are often used for high-performance, tough, elements such as tools for machining.
- Finally, titanium alloys - among the most expensive - are favored for medical applications, such as implants, thanks to their biocompatibility. Due to their high Young modulus/density ratio, they are also used in high-mechanical performance parts, for instance for aeronautics.

A general comment is that cost is obviously *not* a physical properties of the material, and depends on many aspects, from the availability of the ores and raw materials to produce it to global geopolitical considerations, and most of all, the economy.

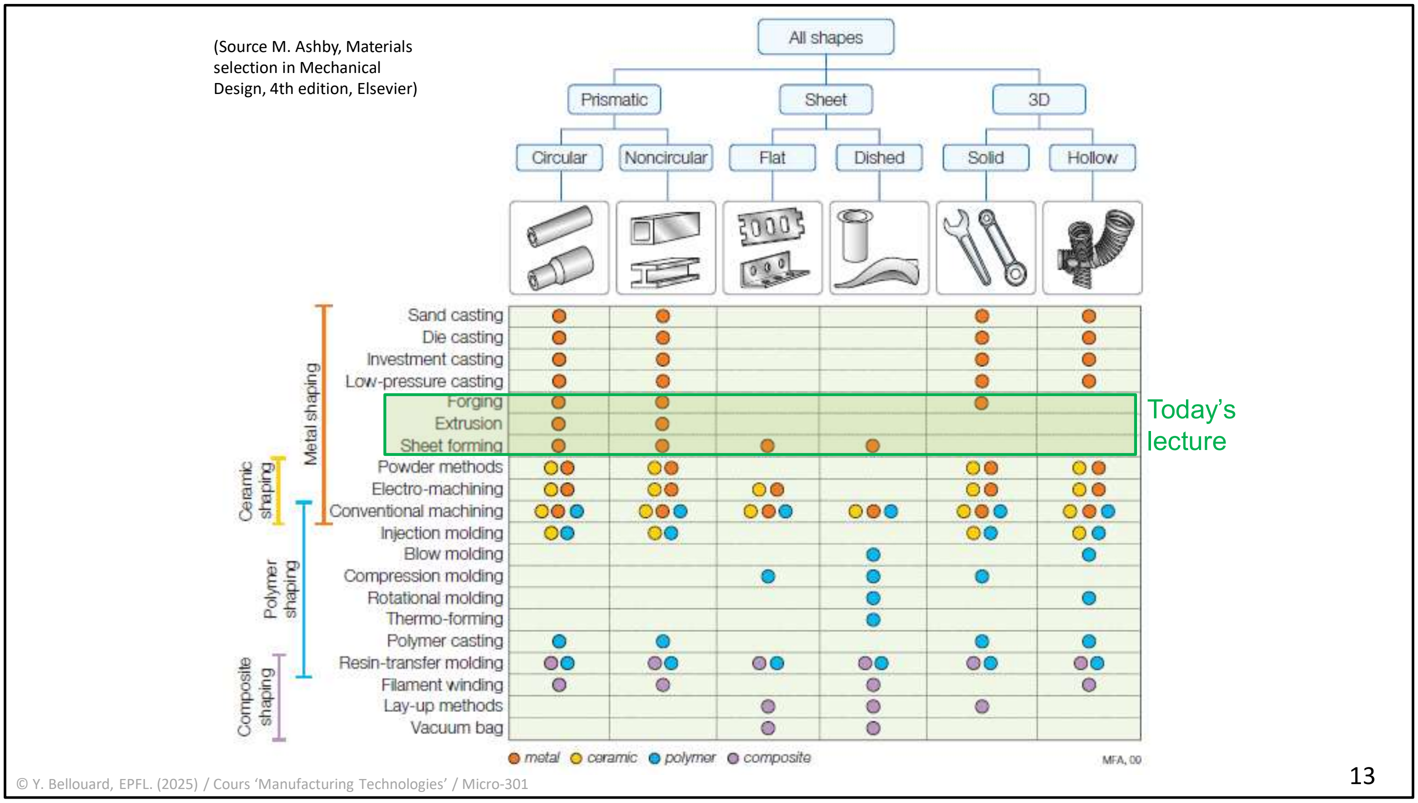


But... relatively high need for energy to produce metals...

(source GrantaDesign – Materials charts)

For a complete picture, let us examine sustainability issues and in particular the amount of energy required to produce the material. In that comparison, metals tend to be not the most frugal materials and among the most 'energy'-demanding materials.

Producing titanium requires hundred times more energy than cast irons, which makes it costly.



(Source M. Ashby, Materials selection in Mechanical Design, 4th edition, Elsevier)

		All shapes					
		Prismatic		Sheet		3D	
		Circular	Noncircular	Flat	Dished	Solid	Hollow
Metal shaping	Sand casting	🟠	🟠			🟠	🟠
	Die casting	🟠	🟠			🟠	🟠
	Investment casting	🟠	🟠			🟠	🟠
	Low-pressure casting	🟠	🟠			🟠	🟠
	Forging	🟠	🟠			🟠	
	Extrusion	🟠	🟠				
	Sheet forming	🟠	🟠	🟠	🟠		
Ceramic shaping	Powder methods	🟡🟠	🟡🟠			🟡🟠	🟡🟠
	Electro-machining	🟡🟠	🟡🟠	🟡🟠		🟡🟠	🟡🟠
	Conventional machining	🟡🟠🔵	🟡🟠🔵	🟡🟠🔵	🟡🟠🔵	🟡🟠🔵	🟡🟠🔵
Polymer shaping	Injection molding	🟡🔵	🟡🔵			🟡🔵	🟡🔵
	Blow molding				🔵		🔵
	Compression molding			🔵	🔵	🔵	
	Rotational molding				🔵		🔵
	Thermo-forming				🔵		
	Polymer casting	🔵	🔵			🔵	🔵
Composite shaping	Resin-transfer molding	🟣🔵	🟣🔵	🟣🔵	🟣🔵	🟣🔵	🟣🔵
	Filament winding	🟣	🟣		🟣		🟣
	Lay-up methods			🟣	🟣	🟣	
	Vacuum bag			🟣	🟣		

🟠 metal 🟡 ceramic 🔵 polymer 🟣 composite

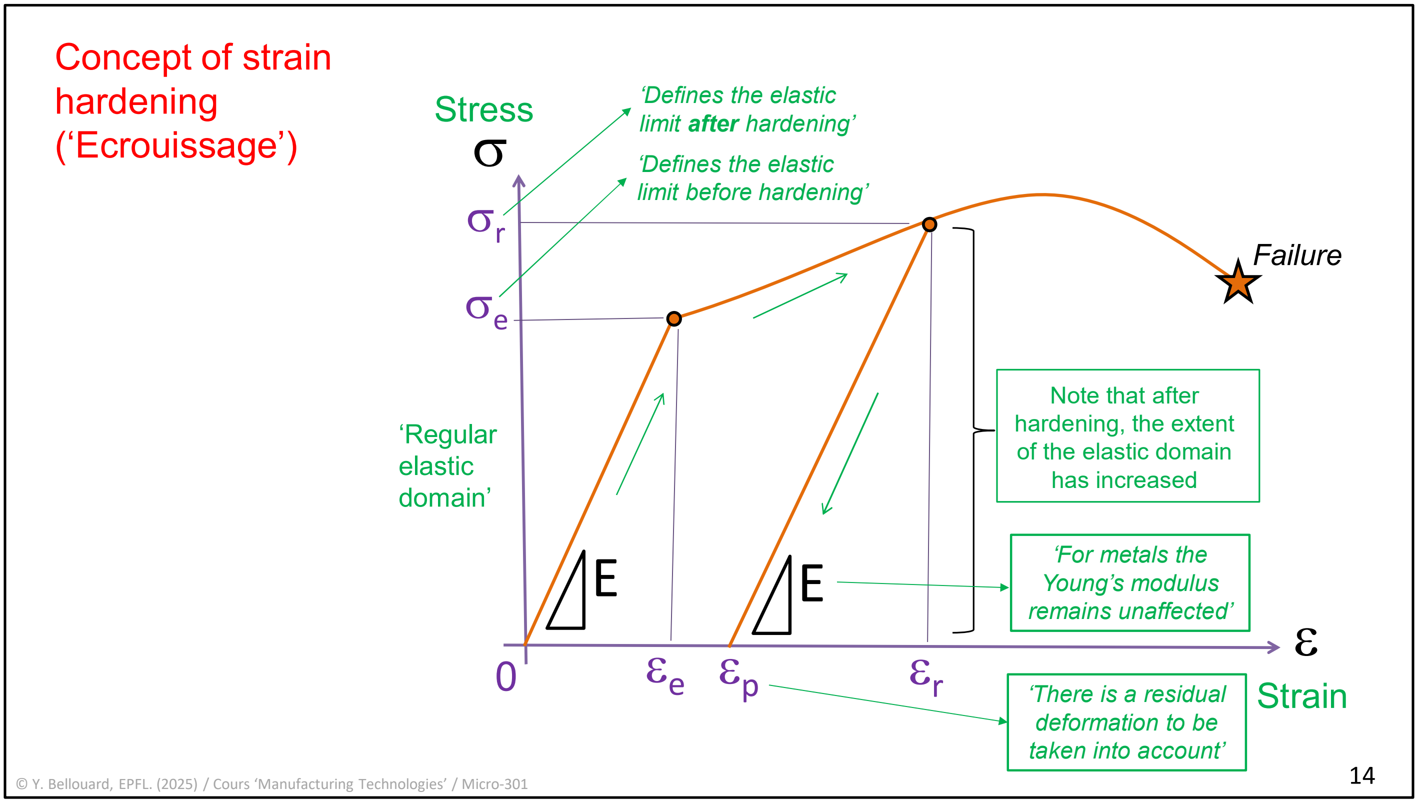
MFA, 00

Today's lecture

Throught the lectures related to the description of manufacturing processes, we will often refer to the table above (from Ashby's book).

This table provides a much simplified view at processes, but remains useful as a tool for a rapid overview at available processes for producing a given shape.

In the sequel, we will now focus mainly on sheet forming and cutting, along with some a brief discussion on forging and extrusion processes.



Concept of strain hardening ('Ecrouissage')

'Defines the elastic limit ***after*** *hardening'*

'Defines the elastic limit before hardening'

'Regular elastic domain'

Note that after hardening, the extent of the elastic domain has increased

'For metals the Young's modulus remains unaffected'

'There is a residual deformation to be taken into account'

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Before deep-diving into forming processes, let us recall the typical mechanical behavior of metals and related definitions. The schematic above shows the main parameters describing a tensile curve of metals, i.e., one a material is loaded under uniaxial stress.

The Young modulus (or elastic modulus) is the slope of the linear elastic domain observed up to a stress level σ_e attained for a deformation ε_e.

Here, σ_e defines the elastic limit before the phenomenon of strain hardening occurs and before plastic deformation starts.

Increasing the stress above σ_e, the material starts to plastically deform. The curve in this regime is described by a strain-hardening empirical law that we will discuss in the next page. As the material is pulled further, the stress keeps increasing up to a limit, where it no longer increase and catastrophic failure of the material occurs.

If the material is unloaded before the maximum stress is reached, the unloading curve follows the *same* linear behavior as observed during the loading in the elastic regime. This is a characteristic of the mechanical behavior of metals.

Once completely unloaded from the plastic regime, a residual deformation is observed (noted ε_p). If the material would be reloaded again from this deformed state, the amplitude of the elastic domain before again plastically deforming the already deformed material will be increased.

Strain hardening ('Ecrouissage')

- When the deformation **exceeds** a certain limit, the material no longer follows the Hooke's law: *'plastic behavior'*
- Various empirical models for the plastic behavior (Swift, Ludwik)
- Ludwik's strain hardening model:

Hardening coefficient

$$For\ \sigma \geq \sigma_e \rightarrow \boxed{\sigma = K\varepsilon^n}$$

Strain hardening modulus (GPa)

$$For\ \sigma \leq \sigma_e \rightarrow \text{Hooke's law}$$

The region of 'strain hardening' can be modeled by empirical laws.

For instance, the Ludwik's strain hardening model shown above, considers two fitting parameters.

A parameter K called the strain hardening modulus (in GPa) and a hardening coefficient n (dimensionless).

The Ludwik model is used for stress above the elastic limit (σ_e), while below (i.e., in the elastic domain), the material behavior is described by Hooke's law.

Ludwik’ strain hardening model

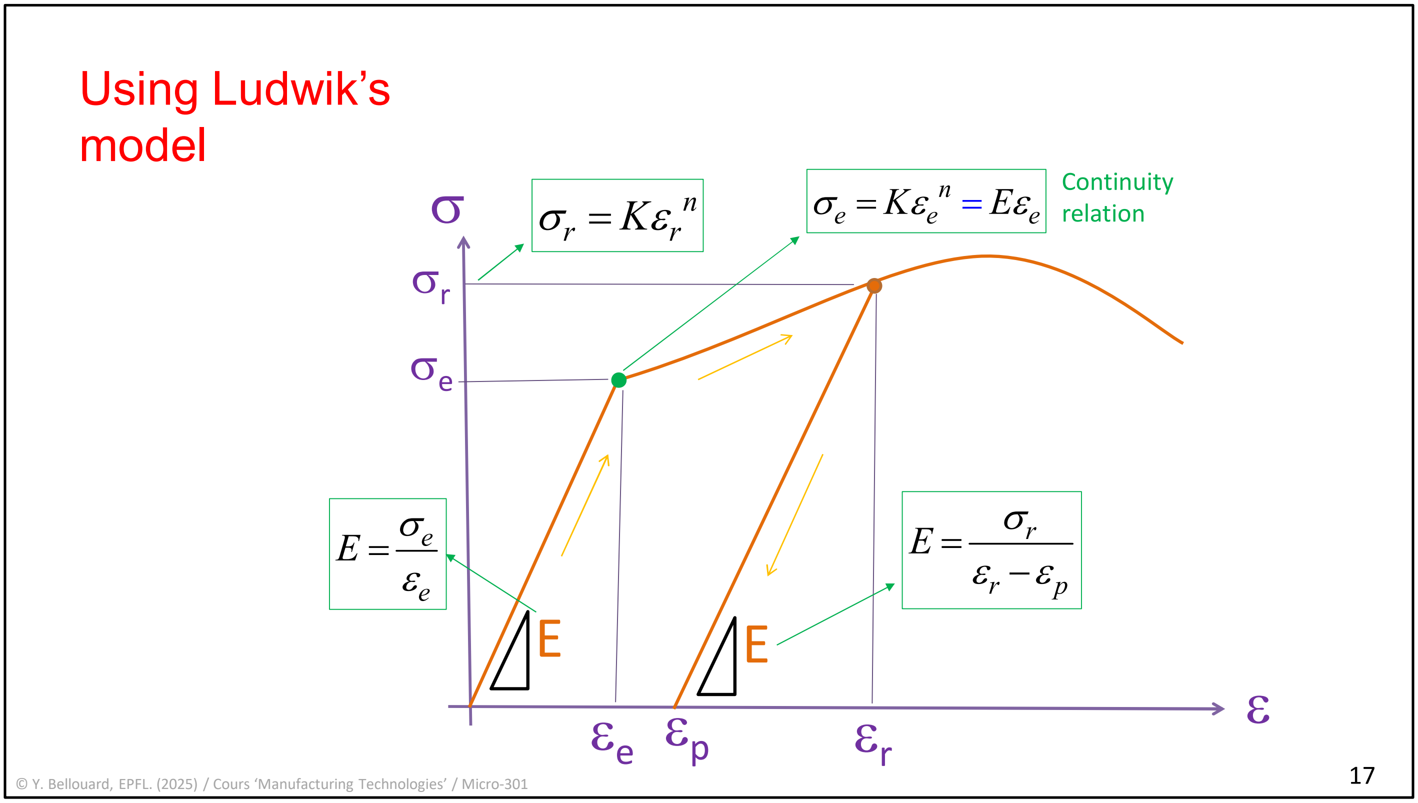
- Compatibility equation with *Hooke’s law* at the point elastic limit point

$$\boxed{\sigma_e = K\varepsilon_e{}^n = E\varepsilon_e \quad \rightarrow \quad K = E\varepsilon_e{}^{(1-n)}}$$

- **0 < n < 1**
- Extreme case:
  - n = 0 → perfect plastic case, $\sigma = \sigma_e$
  (example: Gold, n ≈ 0)
  - n = 1 → ‘the more we deform the material the harder it is…’ (example: Copper, n ≈ 1)

At the point (σ_e , ε_e), the two laws, Hooke’s and Ludwik’s are equal, which provides a mathematical relation between Young’s modulus and strain hardening modulus.

The fitting parameter n varies from metal to metal. For gold, it is almost zero, while for copper it approaches 1.



Using Ludwik's model

$$\sigma_r = K\varepsilon_r{}^n$$

$$\sigma_e = K\varepsilon_e{}^n = E\varepsilon_e$$

Continuity relation

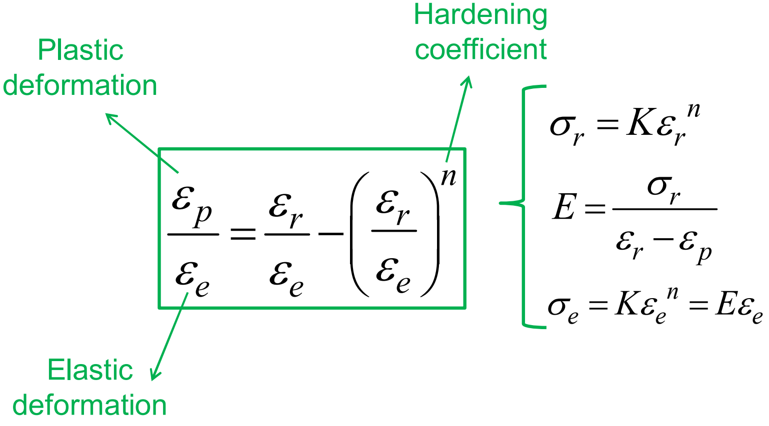
$$E = \frac{\sigma_e}{\varepsilon_e}$$

$$E = \frac{\sigma_r}{\varepsilon_r - \varepsilon_p}$$

Combining Ludwik's and Hooke's law gives a means to relate key points on the curve.

Using Ludwik's model

- Equation to predict the plastic deformation (ε_p) from a residual deformation (ε_r) :



Hardening coefficient

Plastic deformation

$$\boxed{\frac{\varepsilon_p}{\varepsilon_e} = \frac{\varepsilon_r}{\varepsilon_e} - \left(\frac{\varepsilon_r}{\varepsilon_e}\right)^n}$$

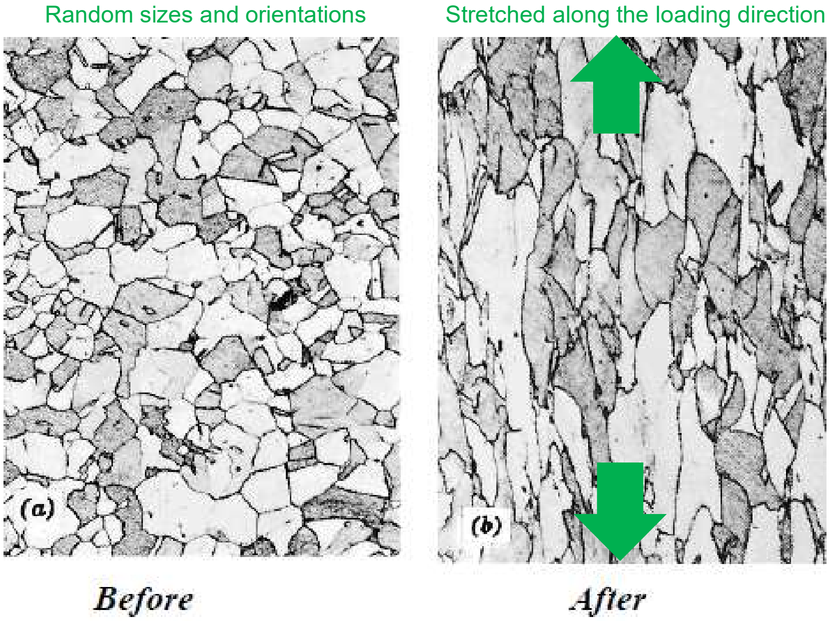
$$\left\{\begin{array}{l} \sigma_r = K\varepsilon_r^{\,n} \\ E = \dfrac{\sigma_r}{\varepsilon_r - \varepsilon_p} \\ \sigma_e = K\varepsilon_e^{\,n} = E\varepsilon_e \end{array}\right.$$

Elastic deformation

Interest: Does not make use of the Young modulus.

As an illustration of these mathematical relations, the plastic deformation can be calculated from the elastic deformation and the residual deformation, knowing the hardening coefficient.

Plastic deformation creates defects in the material…



Random sizes and orientations

Stretched along the loading direction

Defects can be of various types, such as:

- Dislocations
- Deformed grains along the stress
- Texture in the material

(source: Univ. of Tenessee, dept. of Materials Science and Engineering)

The resilience of the material to plastic deformations without fracturing can be related to the ability of the material to deform and to absorb strain energy through dislocations and grains deformations.

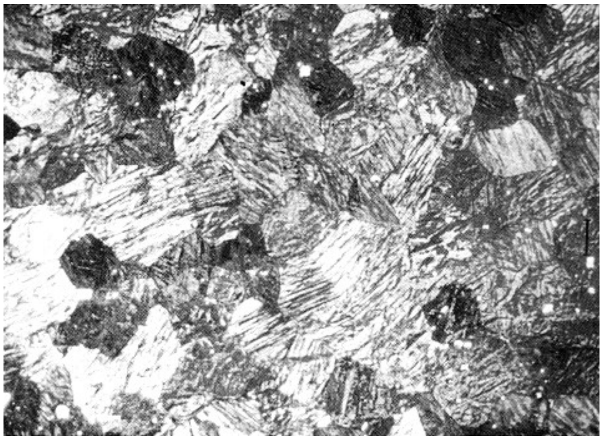
The pictures above illustrate a typical metal structure, consisting of a polycrystal (i.e., an arrangement of small crystals forming grains randomly organized), before and after deformation.

Upon deformation the randomly organized structure tends to be stretched along the deformation direction, thus acquiring a particular texture. Hence, the macroscopic deformation is caused by a microstructural reorganization of the matter.

Example on how mechanical hardening influence microstructures…

‘Random orientations’ → *‘Preferred orientations due to the presence of oriented defects’*

Martensitic variants in Ni-Ti **before** Thermo-mechanical training.



Martensitic variants in Ni-Ti **after** Thermo-mechanical training.

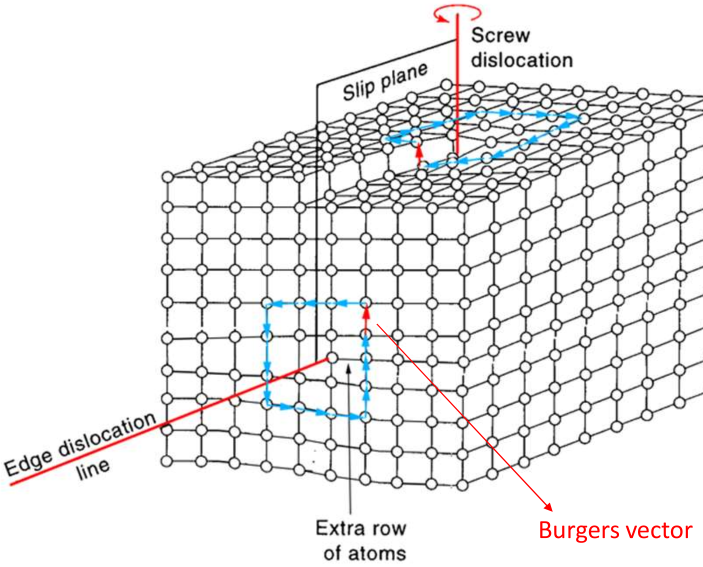
(Source: E. Hornbogen, Bochum Univ.)

Another illustration showing how mechanical deformation and stress influence the microstructure.

Here, we consider a shape memory metal. In the metal grains, there are particular structures called ‘martensitic variants’ (the little elongated structures visible in the grains).

Upon deformation, these elongated structures that are initially randomly arranged (see left image), reorient themselves along the applied deformation.

Dislocations create stress…



Shear modulus

Burgers vector

$$\sigma \propto \frac{Gb}{r}$$

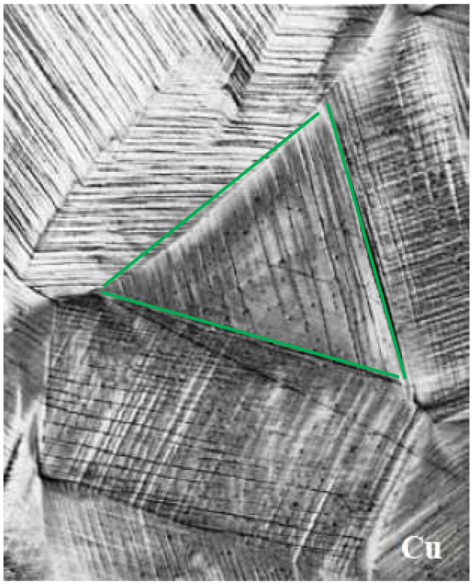
Distance from the dislocation

(source: Univ. of Alberta, Earth and Planetary Science courses)

At the atomic level (inside grains), the formation of dislocations are the cause of internal stress that are source of hardening effects.

Dislocations can be seen as defects introduced in the stacking of atoms as illustrated above. In essence, dislocations can be seen as 'the smallest' defects introduced by macroscopic deformations.

Dislocations

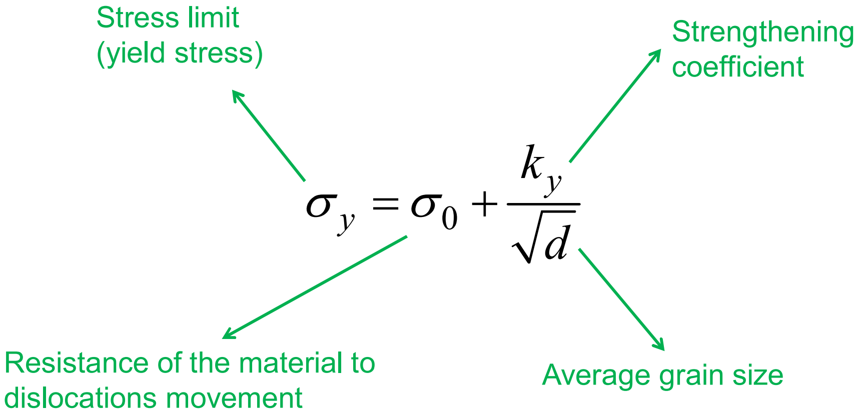


(source: Univ. of Tenessee, dept. of
Materials Science and Engineering)

An electronic microscope image showing a grain with a series of dislocations inside its boundaries.

Hall-Petch: hardening equation

Defines a relation between yield strength and average grain size:



Stress limit (yield stress)

Strengthening coefficient

$$\sigma_y = \sigma_0 + \frac{k_y}{\sqrt{d}}$$

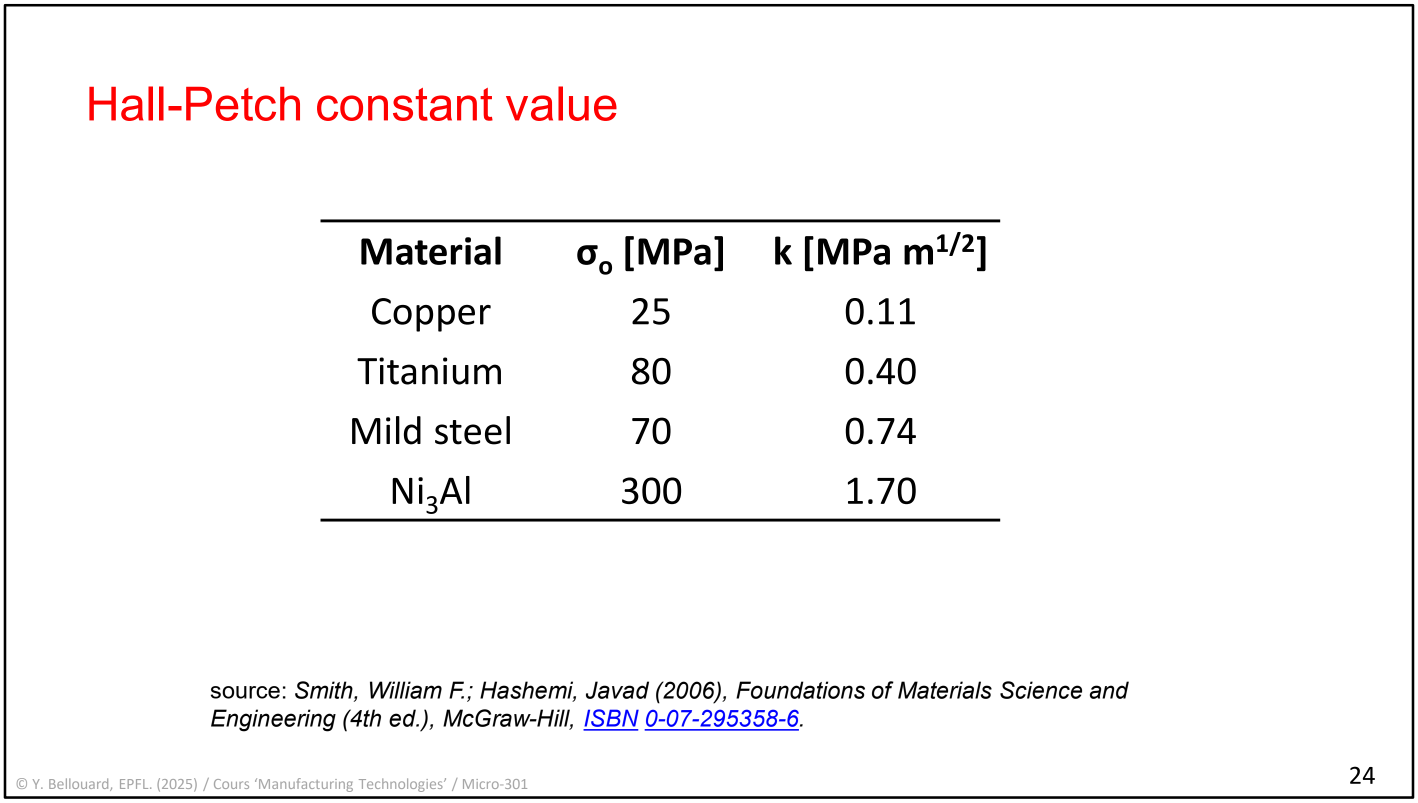
Resistance of the material to dislocations movement

Average grain size

The stress limit (or 'yield stress') can be related to the average grain size, following the Hall-Petch equation.

This equation describes the relation between the average grain size and the yield stress, through a coefficient call the strengthening coefficient. 'The smaller the grains, the higher is the yield stress.'

This important relation shows that there is an intimate relation between grain size and yield stress. In practice, it offers a means to 'engineer' yield stress by controlling the average grain sizes, which can for instance be done through thermo-mechanical treatments.

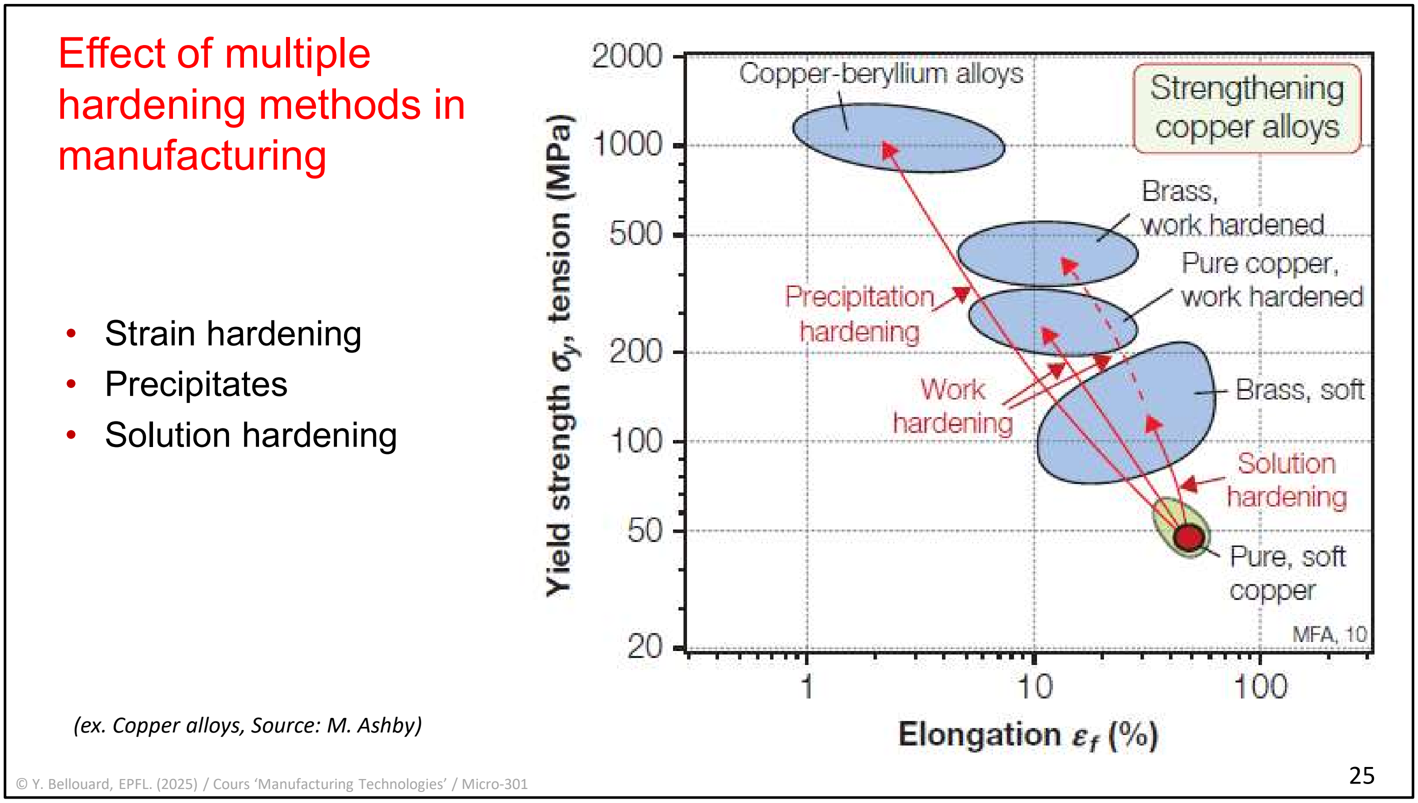


Hall-Petch constant value

Material	**σ_o [MPa]**	**k [MPa $m^{1/2}$]**
Copper	25	0.11
Titanium	80	0.40
Mild steel	70	0.74
Ni_3Al	300	1.70

source: *Smith, William F.; Hashemi, Javad (2006), Foundations of Materials Science and Engineering (4th ed.), McGraw-Hill, ISBN 0-07-295358-6.*

The table above shows a few examples of parameters for the Hall-Petch relation, comparing two pure materials (copper, titanium) with two alloys (mild steel and a nickel-aluminum alloy).



Effect of multiple hardening methods in manufacturing

- Strain hardening
- Precipitates
- Solution hardening

(ex. Copper alloys, Source: M. Ashby)

Hence, metallurgists have a few tools to engineer the properties of metals, and, in particular, their elastic limits.

The graph illustrates this point in the context of copper alloys. Pure copper material has a low yield strength (about 50 MPa) and very high ductility >40 %.

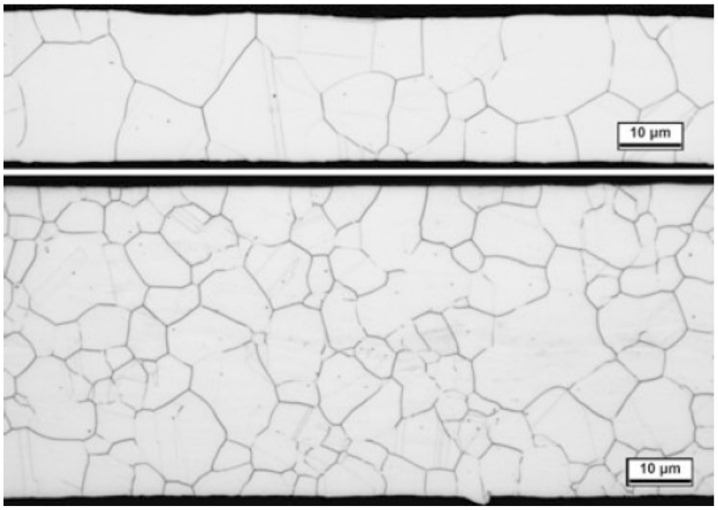
Its yield strength can be increased by various methods:

- By *work-hardening* without changing the composition of the materials. Typically, it can be multiplied by a factor 4 or more.
- By *alloying* to from a new alloys, such as brass (Copper + Zinc alloy). In such case, the yield strength can typically be triple compared to pure copper. By further hardening the brass alloy, level close to 500 MPa can be reached.
- Using *precipitation hardening* (a process that consists of forming precipitates in the material) in a Cu-Be alloy, the yield strength can even reach GPa levels.

Hence, materials engineering offers means for tuning mechanical properties of metals in various ways.

Scaling effect when dealing with thin materials

- Thickness of metals approaches the grain size…



steel sheet of X5CrNi18-10

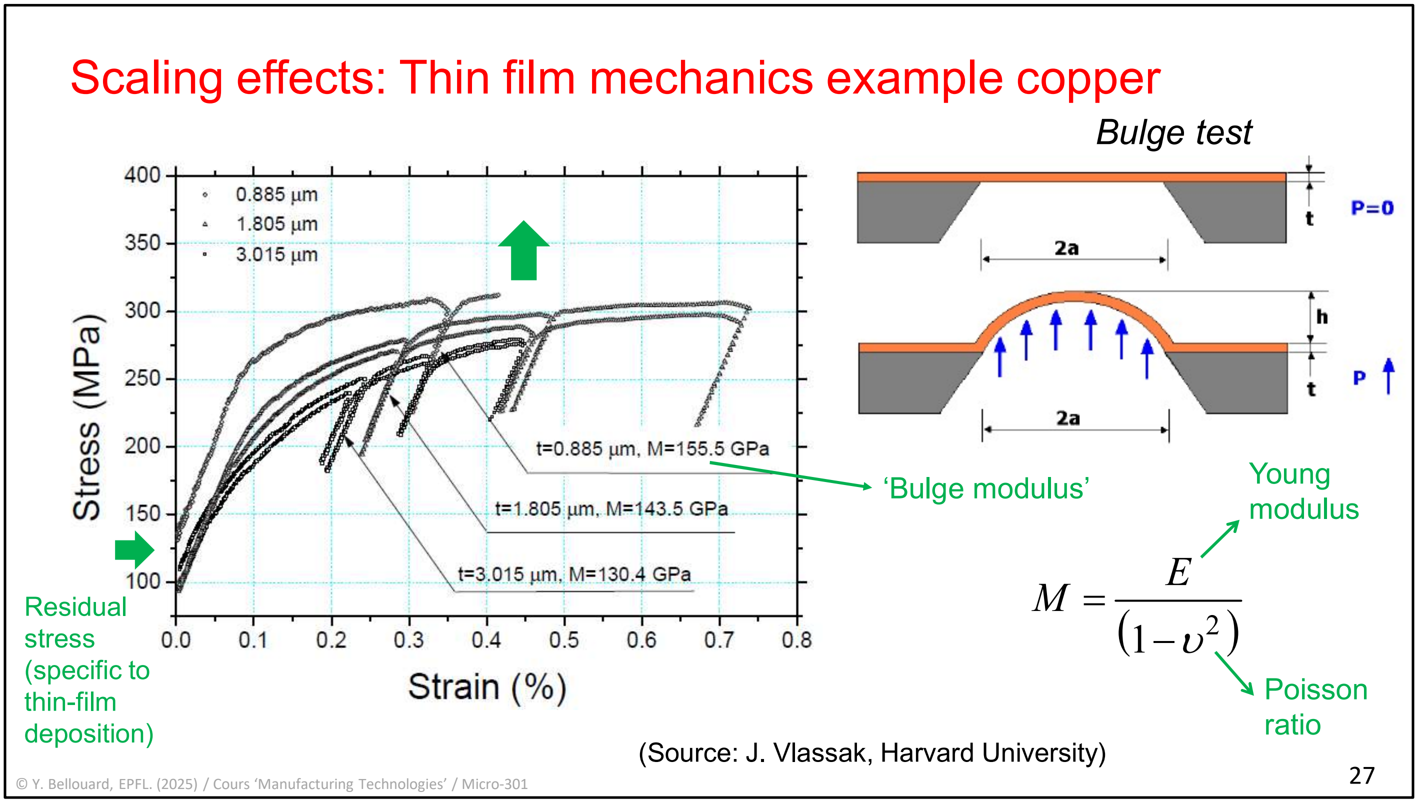
(source: H.W. Zoch)

Finally, another point to consider, particularly relevant in microengineering, is the scaling effect. This aspect is illustrated above. It shows the cross-section of a steel sheet with two different thicknesses. There grain boundaries are revealed (dark lines).

In a polycrystal (*i.e.,* a material made of multiple grains randomly oriented), one can usually assume that the overall properties are somehow averaged in all directions, because of the large number of grains with arbitrary orientation in the same volume.

This assumption is true as long as the grain size is much smaller than the representative dimensions. As soon as the grain size and the characteristic dimension of the material piece starts to be comparable, then one will expect a size-dependent anisotropic behavior to be observed, and consequently, the usual assumption of an averaging effect is no longer exact.

In microsystems in particular, dimensions can be such that conditions where grains size and layer thickness become comparable are met.



Scaling effects: Thin film mechanics example copper

Bulge test

'Bulge modulus'

Young modulus

$$M = \frac{E}{\left(1-\upsilon^2\right)}$$

Poisson ratio

Residual stress (specific to thin-film deposition)

(Source: J. Vlassak, Harvard University)

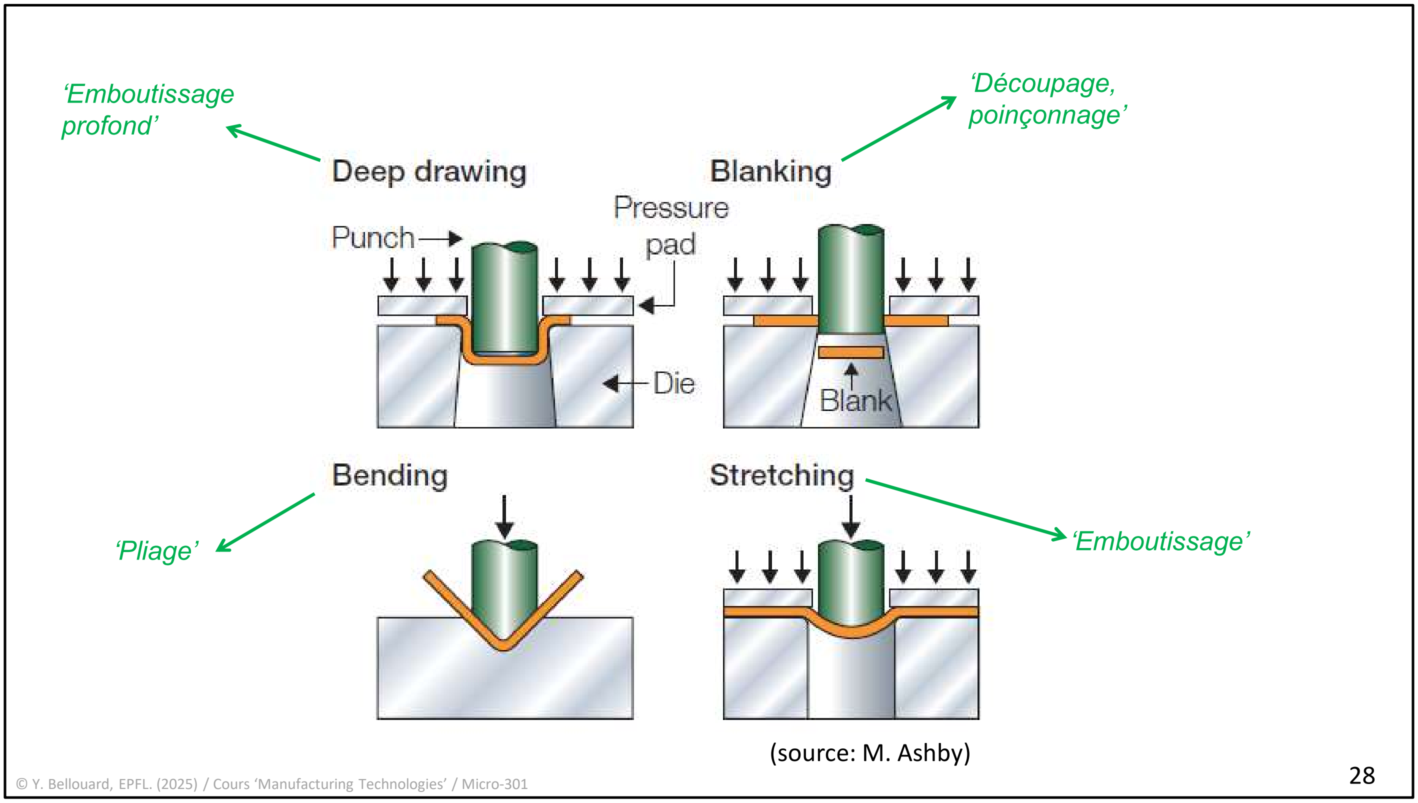
Other effects than the grain size can also be responsible for different behaviors at the micro-/nano- scale. The propagation of dislocations restrained in one direction can for instance modify the overall mechanical behavior.

An example is illustrated in the graph above that considers Cu-films of various thicknesses down to sub-micron levels. There, one can observe that the yield stress is getting higher as the thickness decreases.

As a side note, the picture in the right shows how one can test the mechanical behavior of such thin films. Indeed, unlike larger scale substrates, one cannot simply use a tensile tester, as there is no efficient means for holding such thin substrates without influencing the test.

In the right image, the method shown for mechanical testing is called 'bulge testing'. It consists of producing a suspended membrane on silicon using clean-room methods (such as silicon anisotropic etching and physical vapor deposition processes). The suspended membrane is then inflated by pressurizing the volume beneath it. By controlling the pressure level, the amount of deflection of the membrane can be controlled, which by measuring it, can be used to calculate the strain in the film.

Combined with the knowledge of the pressure, hence the force apply on the film, the mechanical behavior of the film can be measured, just like it would have been done with a conventional tensile tester. The measurements shown in the left graph were obtained using the bulge test method.



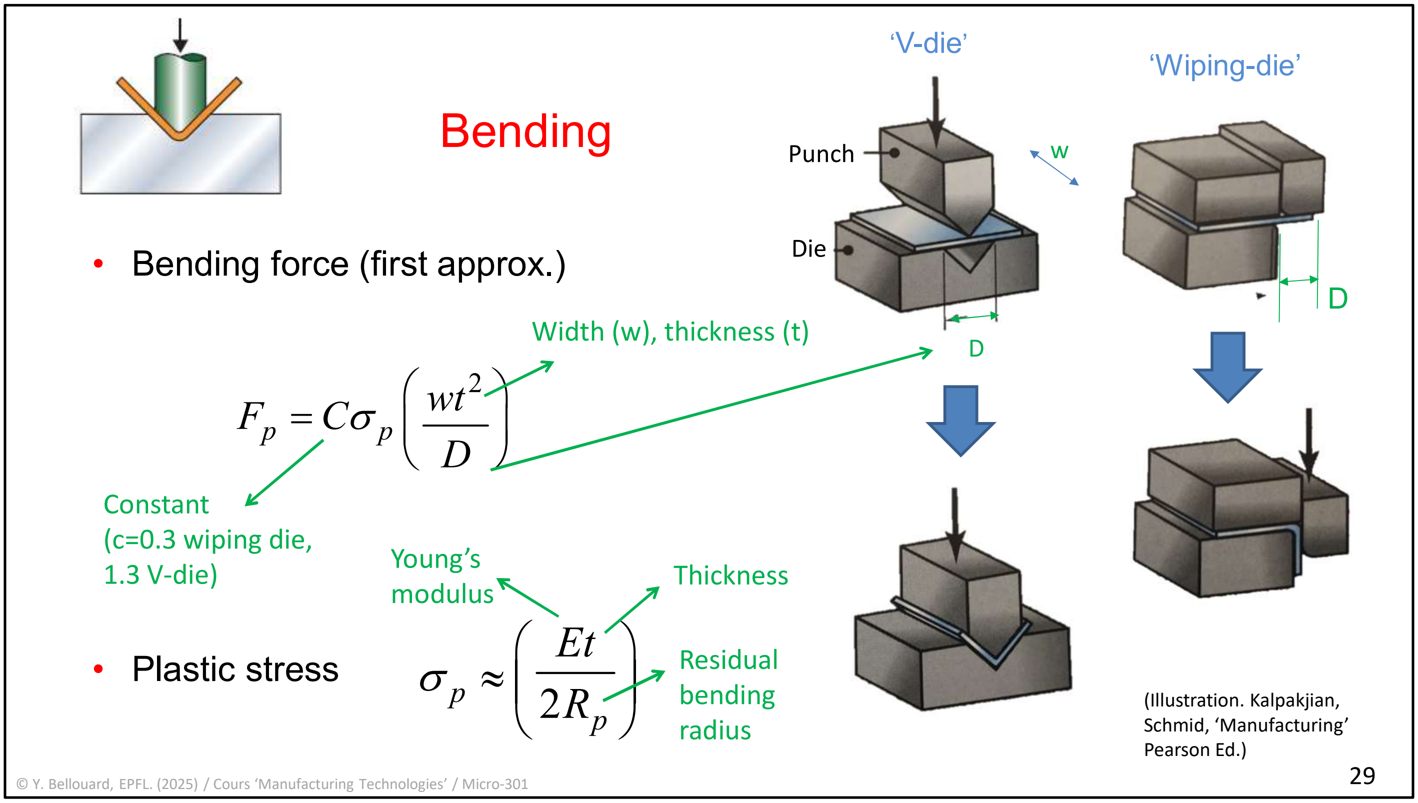
(source: M. Ashby)

Let us now examine the four different methods used to put metals into shape.

There four methods are:

- The **deep-drawing** process (in French: l'emboutissage profond), which consists of stretching the material *severely* by pushing it into a die.
- The **blanking** process (in French: découpage / poinçonnage), which consists of punching out (cutting) a metal piece from a substrate by inducing strong shear-stress on the desired contour of the part.
- The **bending** (in French: le pliage), which is to plastically deform a substrate by pressing it against a preform.
- The **stretching** process (in French: l'emboutissage), which is to deform the substrate by slightly stretching it locally.

In the sequel, we will review the four different methods in details. These four methods are at the basis of the three-dimensional forming of metals.



Bending

- Bending force (first approx.)

Width (w), thickness (t)

$$F_p = C\sigma_p\left(\frac{wt^2}{D}\right)$$

Constant
(c=0.3 wiping die,
1.3 V-die)

- Plastic stress

Young's
modulus

Thickness

$$\sigma_p \approx \left(\frac{Et}{2R_p}\right)$$

Residual
bending
radius

(Illustration. Kalpakjian, Schmid, 'Manufacturing' Pearson Ed.)

Let us start with the simplest process conceptually, the bending.

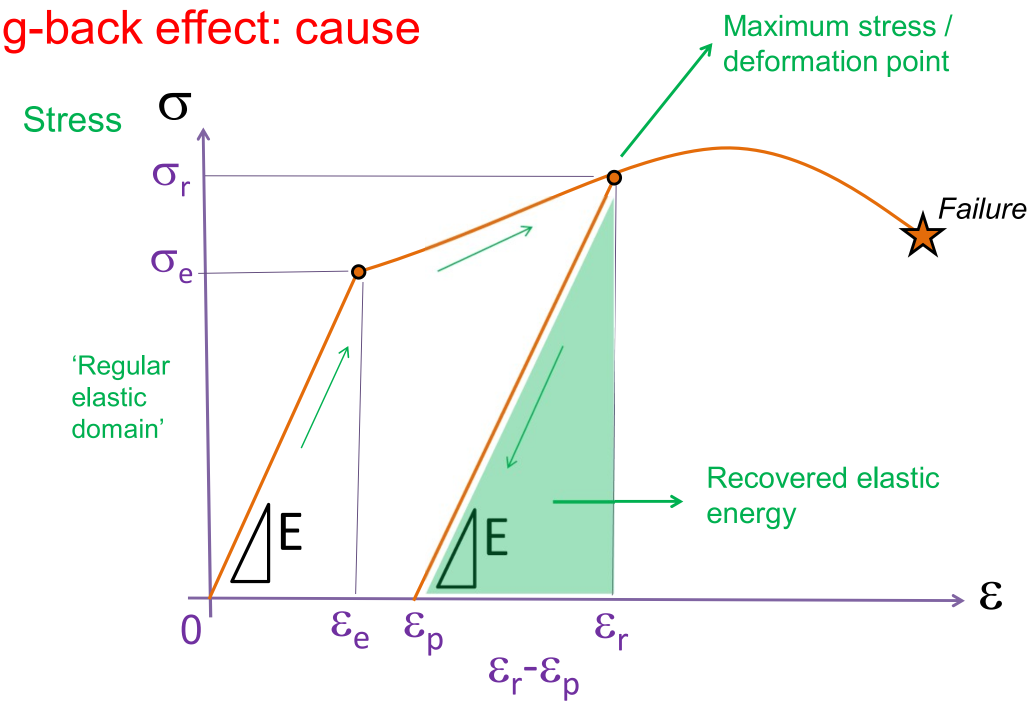
In practice, this operation is realized by pushing the metal part into a die until it is plastically deformed.

To estimate the force required for such operation, let us consider the case of a punch pressing the substrate into a V-groove die. As the substrate is free to move laterally, the loading case is equivalent to a 3-point bending case, and hence, the classical one-dimension equation of beam bending can be used in first approximation.

Using this equation, one can show that the plastic stress is inversely proportional to the residual bending radius (*i.e.,* the radius observed when the part is freed from the die) and linearly proportional to the thickness of the sheet.

To calculate the force required for the bending operation, one can use the generic formula shown above. To accommodate the various type of dies configurations (like the one on the right), different empirical coefficients are used (the constant C).

Spring-back effect: cause

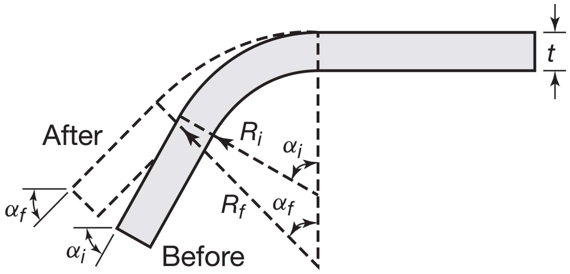


If we go back to the fundamental behavior of a metal subjected to plastic deformation, we have seen in the previous pages that upon unloading from a forced deformed state, the material recovers part of the deformation (due the stored elastic energy).

The practical consequence is that to achieve a designed folding dimension, one have to take into account the 'pull-back' effect, also called **'spring-back'** effect.

This effect is a direct consequence of the mechanical behavior of metals.

Spring-back radius



Spring-back radius

$$R_f \approx \frac{R_i}{\left(4\xi^3 - 3\xi + 1\right)}$$

Bent radius

Yield stress

$$\text{with} \quad \xi = \left(\frac{\sigma_e}{E}\right)\left(\frac{R_i}{t}\right)$$

Young modulus

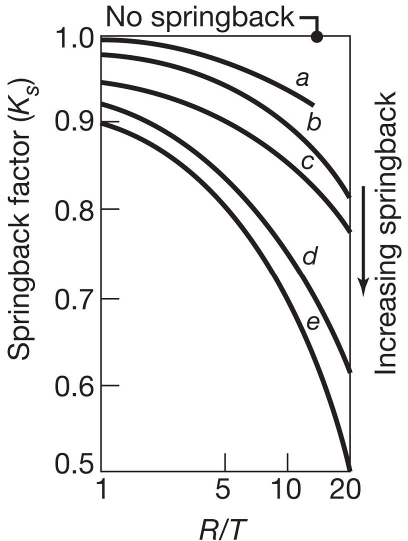
Thickness

(Illustration. Kalpakjian, Schmid, 'Manufacturing' Pearson Ed.)

Limit case, $t << R_i$, $R_f \rightarrow 0$

Using geometrical considerations, the spring-back effect can be calculated, so that the final radius can be estimated from the applied deformation radius using the formula above.

Spring-back factors for various metals



Bending radius to thickness ratio

Spring-back factors

$$K_s = \frac{R_f}{R_i} \approx \frac{1}{\left(4\xi^3 - 3\xi + 1\right)}$$

$$\text{with} \quad \xi = \left(\frac{\sigma_e}{E}\right)\left(\frac{R_i}{t}\right)$$

$K_s < 1$ → The closest to 1 the better.

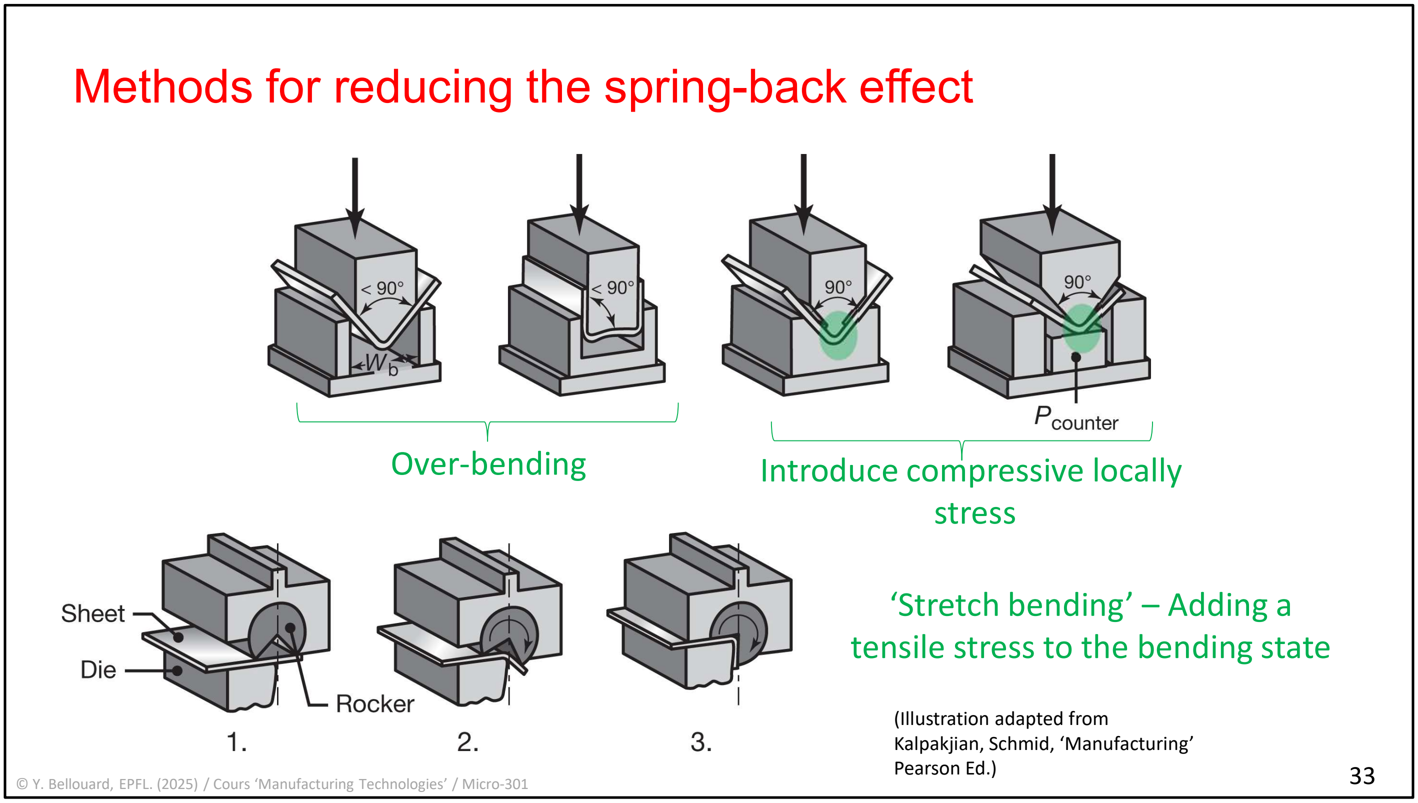
(a) 2024-0 and 7075-0 aluminum; **(b)** austenitic stainless steels; **(c)** 2024-T aluminum; **(d)** ¼-hard austenitic stainless steels; and **(e)** ½-hard to full-hard austenitic stainless steels.

Source: G. Sachs.

The graph in the left shows a normalized representation of the spring-back effect for various metals, from very ductile (case a – aluminum) to barely ductile (case e – austenitic stainless steels).

The closest the ratio K is to 1, the better. As expected, we observe that a more ductile metal reduces strongly the spring-back effect, although it cannot totally suppress it.

Hence, as the spring-back effect cannot be completely suppressed, the question is then to find how we can mitigate it by engineering means.



Methods for reducing the spring-back effect

Over-bending

Introduce compressive locally stress

'Stretch bending' – Adding a tensile stress to the bending state

(Illustration adapted from Kalpakjian, Schmid, 'Manufacturing' Pearson Ed.)

To this end, various methods that are illustrated above have been proposed.

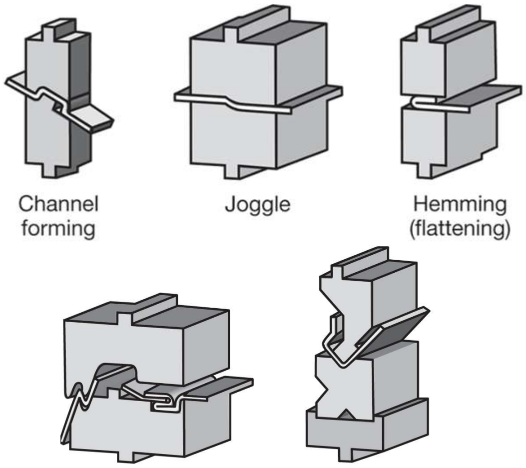
The first one is somewhat intuitive. It consists of 'over-bending' the sheet metal by calculating the necessary over-bending radius to reach the final desired radius.

A second method is to add compressive stress locally at the point of bending. This additional compressive stress further deforms locally the material, introducing a two-dimensional stress-state in the material. It can be achieved by introducing a stress-concentration locally in a two-die design, or by using a counter-die to apply a pressure in the bent region, once the material is bent.

A third method is to add tensile stress during the bending. This is achieved using a 'rocker', a sort of cut cylinder that rotates in the die as the bending pressure is applied. As the die moves down and start deforming the sheet, the edge of the rocker prevent the sheet from sliding (as it would normally do), and doing so, introducing a uniform tensile stress component through the sheet thickness in addition to the bending stress.

Schematic illustration of a press brake

Various dies are used to create complex shapes and folding sequences



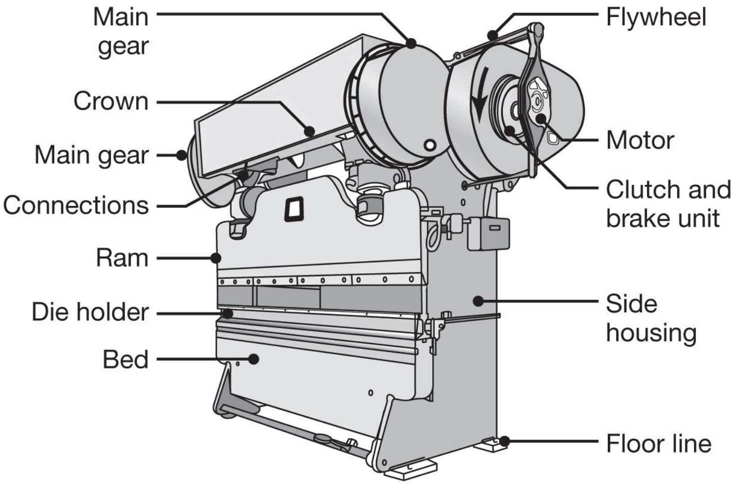
Channel forming

Joggle

Hemming (flattening)

Two-stage lock seam

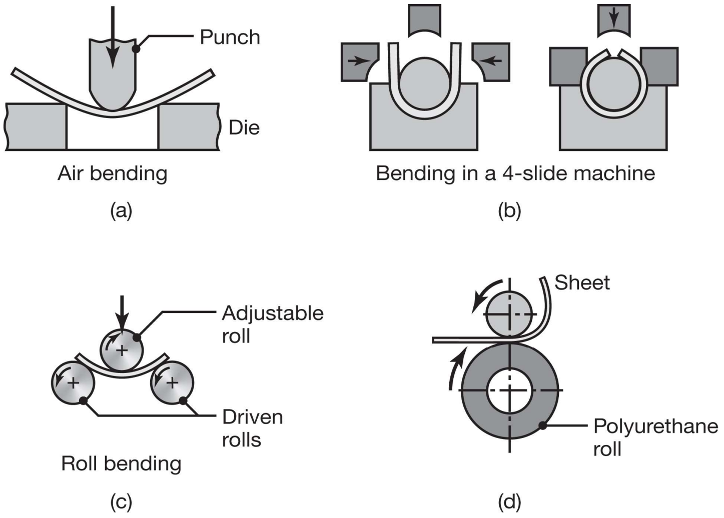
Offset forming



Dies can have various shapes depending on the folding operation to be achieved. The figures in the left illustrate a few examples of dies with sophisticated geometries.

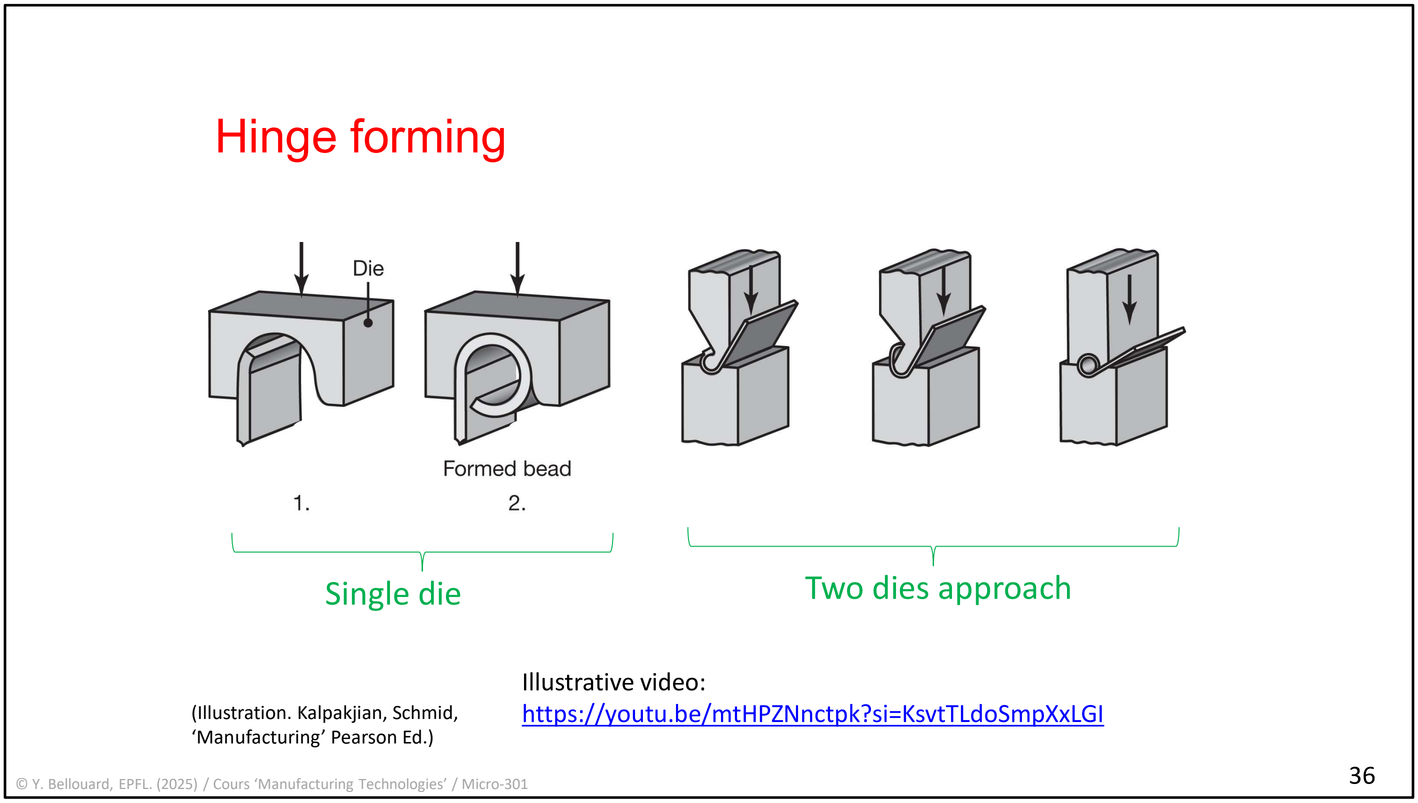
The figure in the right shows a machine using for folding operation, capable of performing sequential folding operations. A closer look at these machines is proposed in the videos in the next pages.

Examples of various bending operations.



Folding operations are not necessarily only made with dies. It can involve rollers, multiple dies acting in synchronized manner, etc.

At the end, it remains the same principle for forming metals. What differs is only the way the deformation is applied.



Hinge forming

Single die

Two dies approach

(Illustration. Kalpakjian, Schmid, ‘Manufacturing’ Pearson Ed.)

Illustrative video:
https://youtu.be/mtHPZNnctpk?si=KsvtTLdoSmpXxLGI

As an illustration, the example above illustrates how a door hinge can be made by metal-sheet forming.

One version is to push the metal sheet in a single die shaped as a cylinder. A second approach is based on a two-die folding principle.

Illustration

(courtesy UKB) https://youtu.be/eLVjqfOmobQ?si=YSjzLfByKGOZpaCi

Another video illustration of various beam folding operations.

Example of bent / blanked / stretched parts…

https://www.wrico-net.com/

Metal forming is used in countless number of applications. Many of which, you are probably familiar with.

Hence, it remains one of the most important manufacturing process to be aware of.

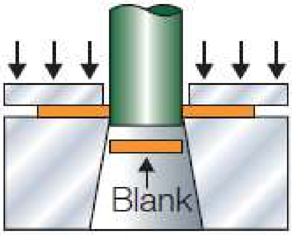
Small scale stamping / bending…

(Source: Fa. Harting GmbH & Co, Germany)

A process very used and in very diverse applications!

Although it may sound more adapted to large scale object, it is in fact very used at the smaller scale too. Electronics connectors such as the recently introduced micro-USB connector are a typical examples.

Stamping is also extensively used in the watch industry, with some features size being as small as a few tens of microns.



Analysis: Blanking

- *En français: 'découpage' ou 'poinçonnage' suivant la pièce conservée à la fin.*
- Approximation: pure shear stress state
- If **L** is the contour of the part, **t** its thickness, $\mathbf{t_c}$ the already cut thickness:

Cutting force

$$F_{blanking} \approx \tau_c \left[L\left(t - t_c\right) \right]$$

Shear stress for cutting
> rupture stress

Contour of the part
being punched out

Initial thickness

Cut thickness

Often combined with beam forming is the process of 'blanking' (sometimes also referred as stamping). There a piece of material is 'cut' away from a sheet metal.

The fundamental principle is to apply a shear stress (in French: 'contrainte de cisaillement') on the contour to be cut. As a reminder, shear stress corresponds to the case where two opposite coplanar forces are applied in a direction corresponding to the cross-section of the material.

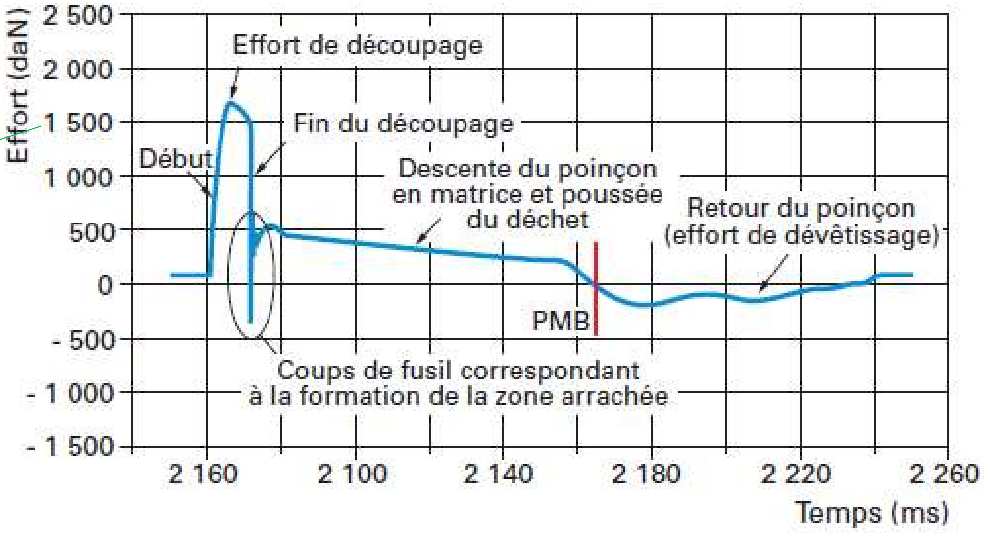
If this shear stress exceeds the ultimate stress limit of the material, the material will yield and be cut along the contour of the tool.

To visualize the process, one can think of a paper puncher to make holes. The idea is somehow similar, but adapted to metals and to arbitrary contours.

The force to apply to cut a part along a contour of arbitrary length L is proportional to the ultimate shear stress limit times the thickness to cut. The force is not constant as the sheet metal is gradually cut and evolves dynamically. This force component, if not controlled, can introduce a characteristic localized bending of the part need the cut region.

This dynamic effect is further described in the next page.

Typical force profile during blanking



Tons!

(Note: daN=deca-Newton 'kgf')

(Source A. Maillard, Technique de L'ingénieur, BM 7500)

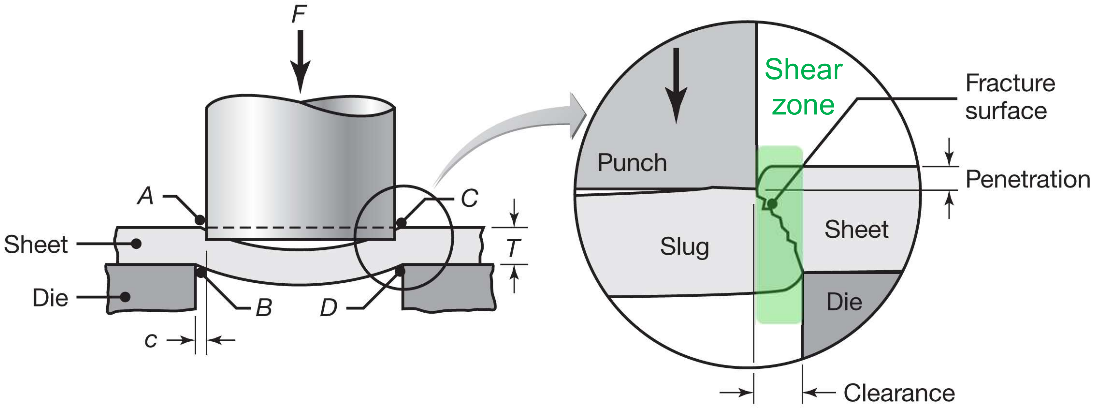
Graph showing how the blanking force evolves during the cutting process.

It first ramps up steeply until the force reaches the material plastic limit, then diminishes as the material starts yielding, and ultimately, until the material is cut.

There, the force abruptly decays. Due to the cutting machine inertia, a violent recall force is observed.

As the stamp moves further down, a friction force is observed, followed by a similar force (but inverted) when the stamp is removed from the part.

Shearing process in a dye



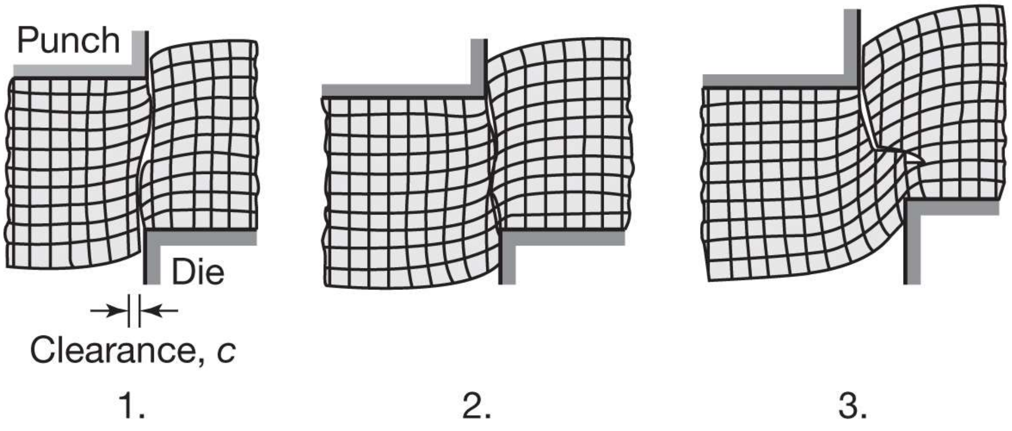
Source: Serope Kalpakjian | Steven Schmid, *Manufacturing Processes for Engineering Materials,* Sixth Edition, Pearson Ed.

Let us take a closer look at the shear zone.

Theoretically, a perfect shearing would mean that opposing forces are separated by an infinitely small space and almost aligned with one another.

This would mean that the clearance between the puncher and the die would be almost zero, which is unpractical as parts have tolerances.

Effect of clearance between punch and die



Increasing clearance between punch and die

(adapted from H.P. Weaver and K.J. Weinmann.)

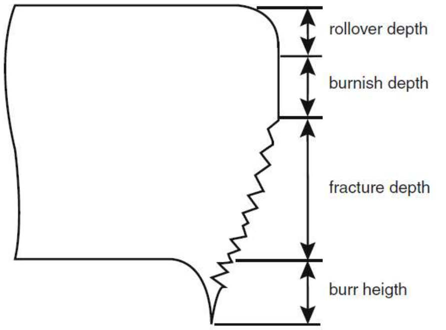
As the clearance between the puncher and the die cannot be infinitely small, it means that, in practice, an imperfect shear loading state is applied.

Naturally, the bigger the clearance, the more the loading case departs from the pure theoretical shear-loading case.

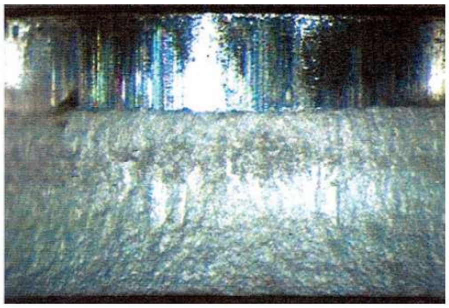
This point is illustrated above that shows the shape of the material deformation for increasing clearance between the punch and the metal sheet.

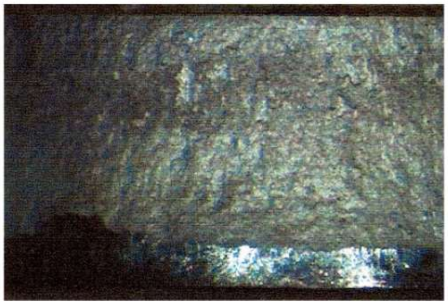
As the clearance is increased, one can appreciate how the shape of the deformed material departs from an ideal pure straight cut.

Typical morphology of blank profile



(source G. Behrens)





Ejected part

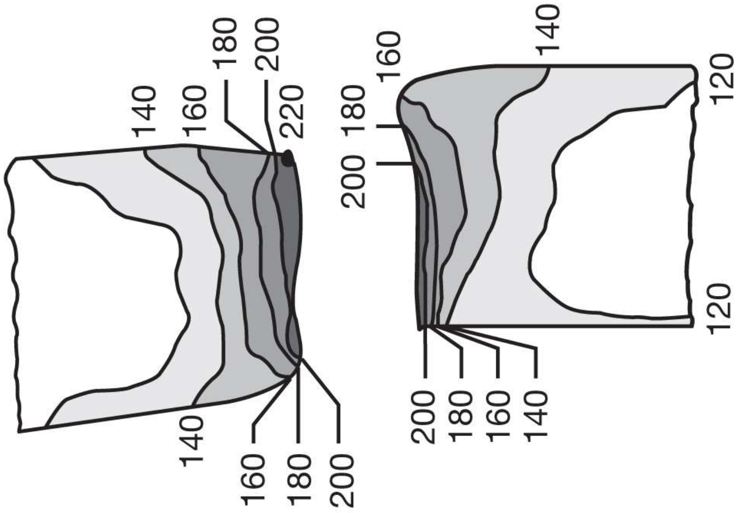
(Source A. Maillard, Technique de L'ingénieur, BM 7500)

During cutting, and because of the presence of a non-negligible clearance between the puncher and the sheet, the fracture profile evolves dynamically as the cut progresses, leaving a distinguishable and easily recognizable morphology on the cut surfaces.

It first starts by a clear cut ('burnish depth') until the deformation progressing towards a material being torn apart, which create another type of fracture morphology.

Hence, having a close look at the edge of metal parts can provide hints about the process that has been used to fabricate it.

Strain-hardening effect: illustration



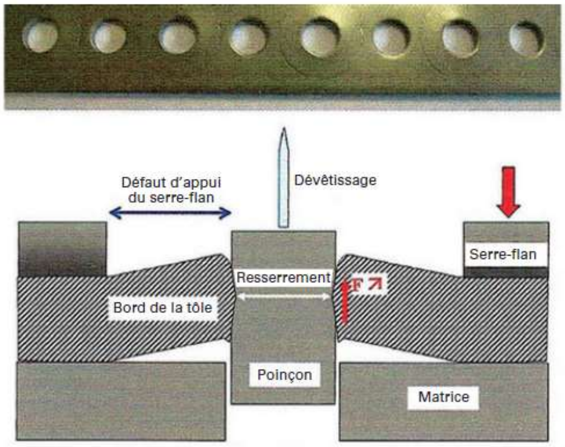
Microhardness (HV) contours for a 6.4-mm thick AISI 1020 hot-rolled steel in the sheared region. *Source:* After H.P. Weaver and K.J. Weinmann.

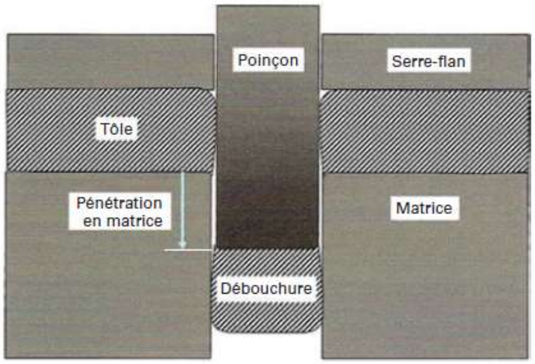
The cross-section above illustrates micro-hardness measurements (see lecture on surfaces) performed on cut regions.

As the cut originates from a severe mechanical deformation - first plastically deforming the material until it reaches its yield stress limit before rupturing, a strain hardening effect can be observed near the cut surface.

Consequently, and perhaps counter-intuitive, the cut surfaces will have a higher mechanical resistance than the untouched sheet surfaces.

Importance of the clamping element





(Source A. Maillard, Technique de L'ingénieur, BM 7500)

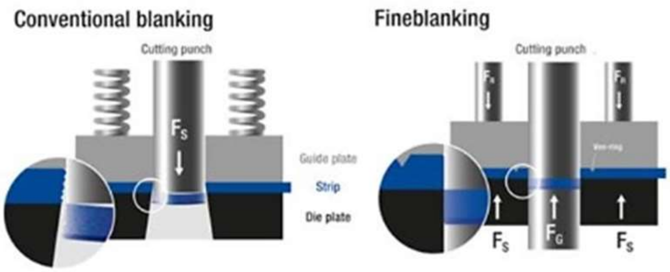
In practice, when the puncher moves into the material and then retrieved, friction can cause the material to locally deform as the puncher moves out of the sheet metal (see curve about the force applied during metal cutting).

This effect may be undesired as it creates a locally deformed shaped around the cut, like here around the holes in the picture above.

To prevent this effect, in precision cutting operation, the metal sheets is clamped in between a die and guiding plates that hold firmly the sheet while being cut and until the puncher is moved out.

This technique is referred as 'precision blanking'.

Fine blanking versus conventional blanking



(illustration: Swisstec.com)

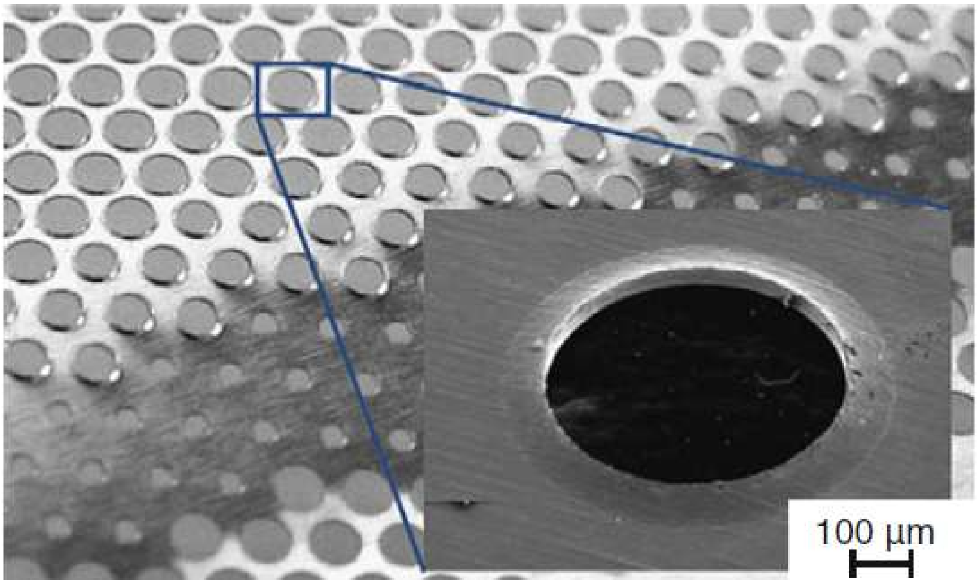
Fine Blanking Normal Stamping

(Illustration: dsfinetec.com)

- Goal is to better confine the stress to achieve purer shear stress loading
- Requires a more complex tooling
- Counter force and v-grooves to prevent sliding

A detailed description of the precision blanking process.

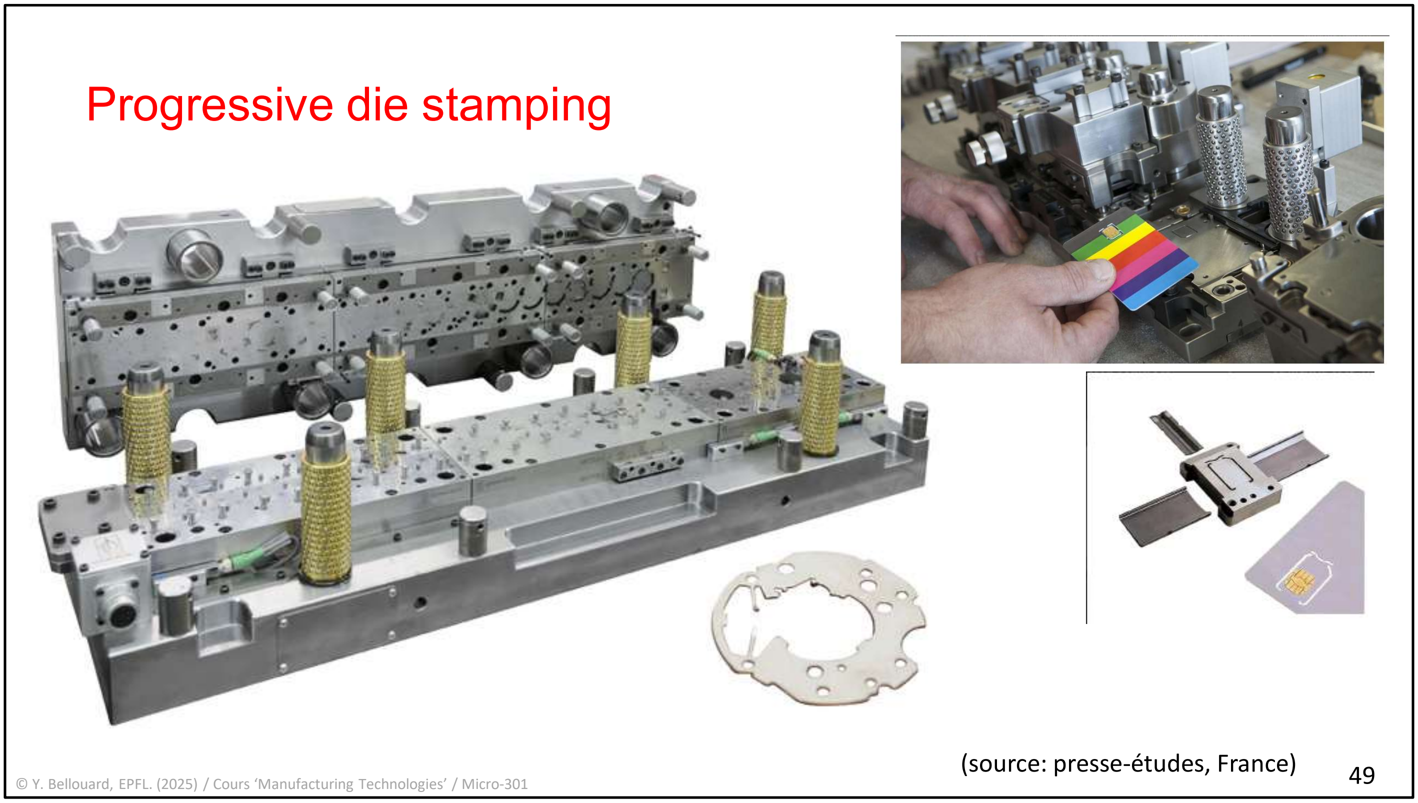
Example 'micro-blanking'



(image: Shaving foil, G. Behrens)

Just like forming, blanking can also be applied at the smaller scale. Here, a blanking process is used to produce shaving grids.

The holes have a characteristic deformed state (as seen above), which is used here as an advantage, as the cut is naturally folded towards the inside, preventing a risk of arming the user as the shaving grid slides on the skin.

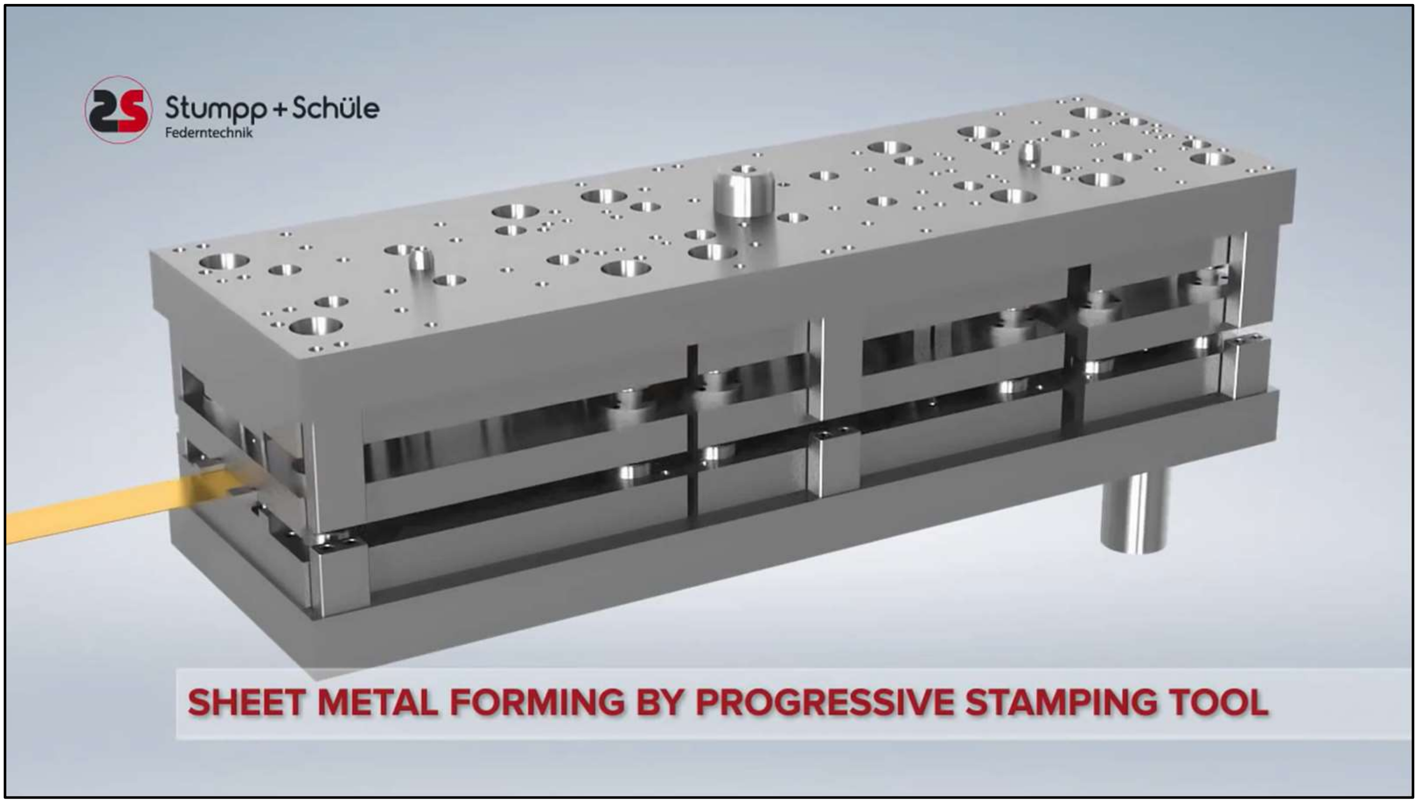


Progressive die stamping

(source: presse-études, France)

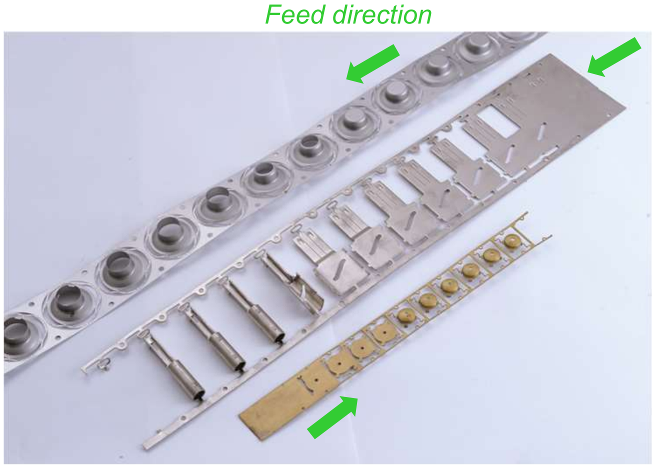
Blanking, embossing, folding, and alike to produce micro-parts are often used sequentially in a single machine defining a process called '*progressive die-stamping*' (in French, 'étampe à suivre').

The picture above shows a typical tooling for progressive die-stamping operations to produce complex parts. This important process – very used in manufacturing - will be further detailed in the next pages.

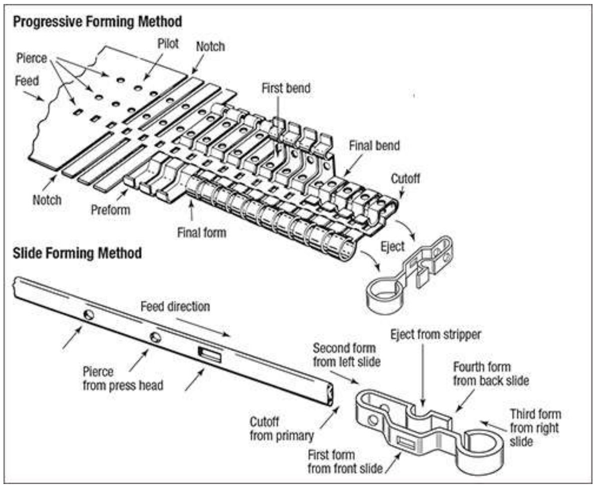


A video illustrating the progressive stamping operation. (The video can be found in the Moodle.)

Progressive die-method illustrations



(source: Camfas international)



(source: MetalForming Magazine)

In progressive die-stamping operation, a sheet metal, in the form of a strip with indenter holes, move sequentially through the progressive stamping tool.

Each discrete indent defines a process operation, that can be a folding, a cutting or an embossing step for instance.

The picture in the left illustrates how a part is gradually put into shapes through sequential operations of cutting and folding.

The sketch in the right further shows how a clever sequence of forming operations can produce a complex metal parts with intricated details. It shows the example of a metal strips connector elements found in electrical devices.

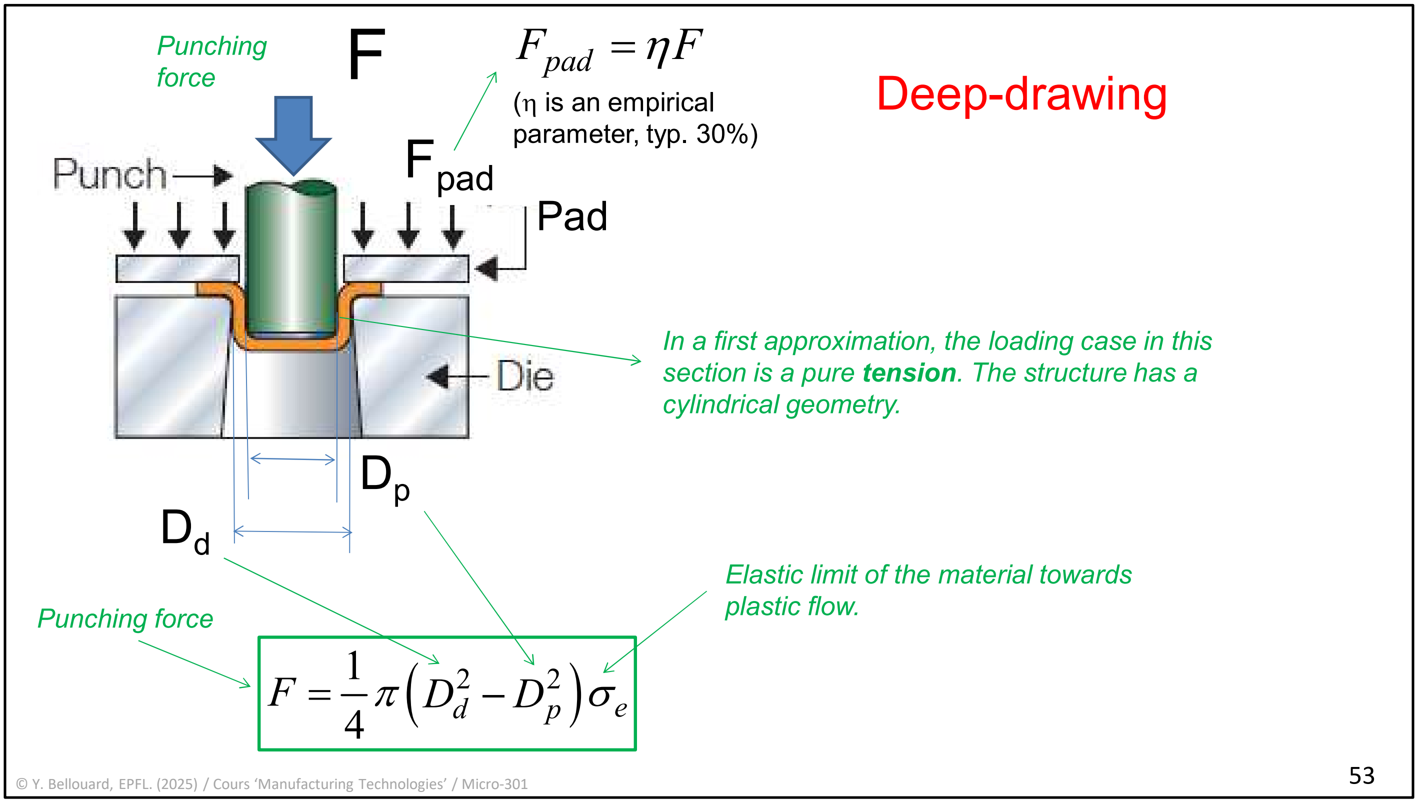
Progressive die-stamping

Additional illustration:
USB-C connector:
https://youtu.be/undjyNPIk0I?si=JqgTfGr01P3AcRIv

Source Scandic: https://youtu.be/U8d3YCtr5pA?si=2FWZvoDiDVCrOsNV

The two videos further illustrate examples of *progressive die-stamping* processes used to produce complex parts, such as micro-USB connectors.

Progressive die-stamping is very used for large scale production, like for instance, parts produced in the hundreds of thousands to millions or even billions (like for USB connectors).



Deep-drawing

Punching force

$$F_{pad} = \eta F$$

(η is an empirical parameter, typ. 30%)

*In a first approximation, the loading case in this section is a pure **tension**. The structure has a cylindrical geometry.*

Elastic limit of the material towards plastic flow.

Punching force

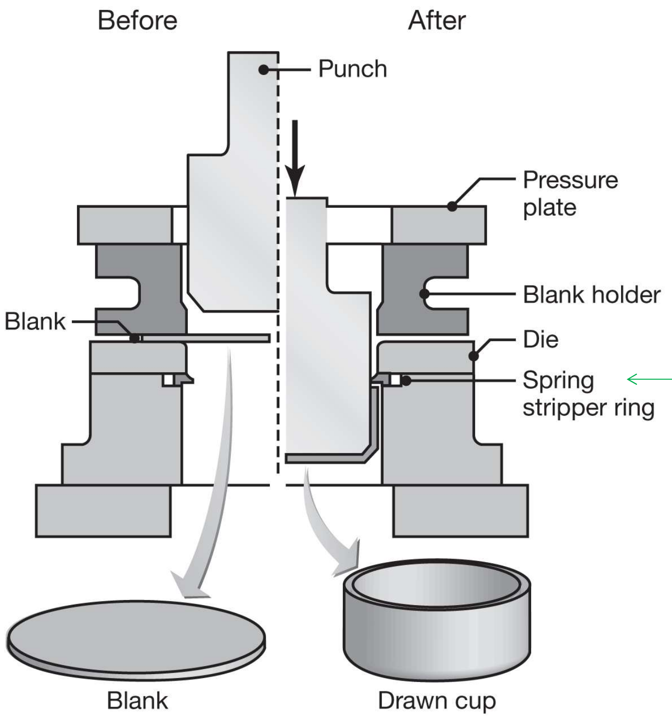
$$\boxed{F = \frac{1}{4}\pi\left(D_d^2 - D_p^2\right)\sigma_e}$$

Deep-drawing also belongs to the category of metal forming process. There, the principle is to stretch heavily a metal through a ductile deformation to form a cylindrical shape.

In practice, a blank is severely deformed by a puncher that stretches it through a die, while a pad retaining the blank edges as the metal is sliding in.

As the metal is essentially loaded in tension at a stress level passed its elastic limit, the punching force can be estimated simply as the force applied to a surface defined by the rings between the die and the puncher.

Deep-drawing in practice



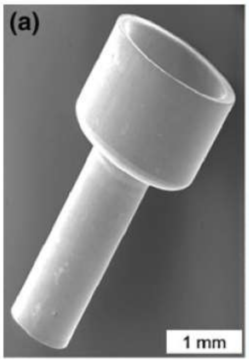
To prevent the part from sticking to the punch

- Illustrative videos:
  - Fabrication des bouteilles de gaz: https://youtu.be/InQbKm3AU1A

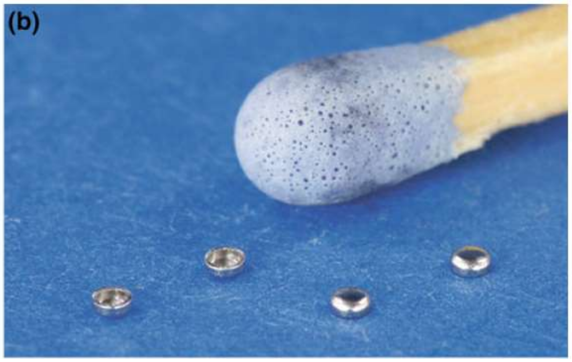
Deep-drawing is typically used for producing metal bottle (like the SIGG bottles – see first lectures video), gas bottles or the beverage cans.

The illustration above shows some fine designed details used in practice in a deep-drawing setup. For instance, a spring stripper ring is used to retain the drawn shape as the punch is moved back up at the end of the deep-drawing operation.

Deep-drawn ‘micro-parts’



(image: U. Engel)

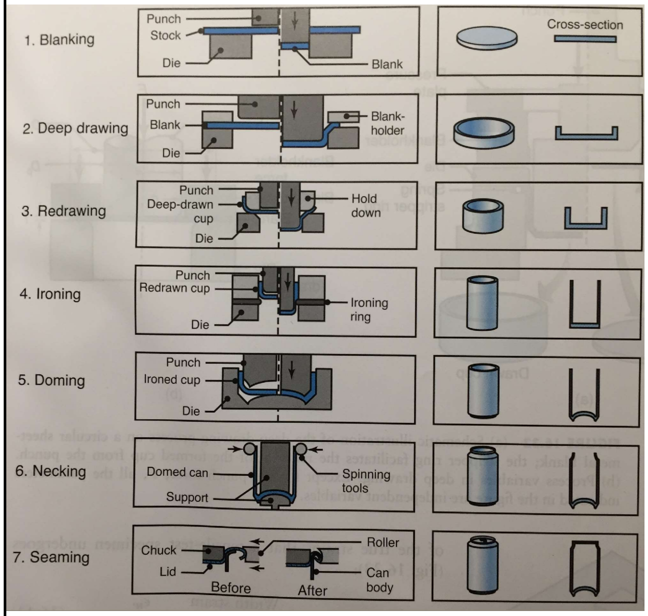


(image: Stüken GmbH & Co)

(source: Wafios GmbH)

Although deep-drawing is commonly used for large parts, it is also used at the smaller scales, as shown above. For instance, the process of deep-drawing heere is used to produce copper electrical pins.

Example of complex forming



(image: dinkstuff.com)

(Illustration. Kalpakjian, Schmid, 'Manufacturing' Pearson Ed.)

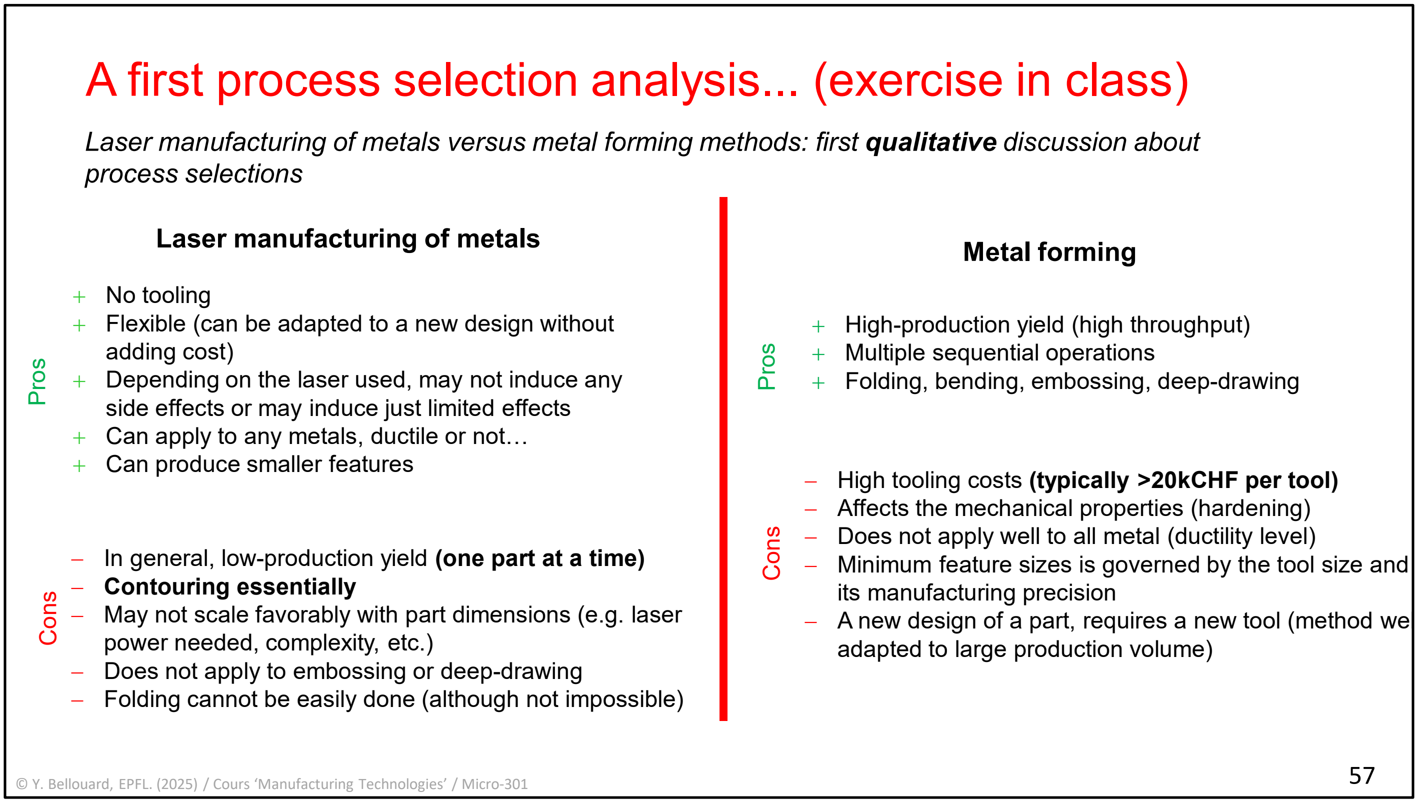
Production:
~ 15000 /s worldwide

Recommended excellent video about reverse engineering on the beverage can: (Prof. Bill Hammack, Univ. of Illinois)

https://youtu.be/hUhisi2FBuw

An iconic illustration of hot embossing is the beverage can that is produced in very large quantities (about 15'000 cans are produced every second worldwide). The sequential steps to produce the can are illustrated in the left image.

We strongly encourage you the watch the video above (also in the Moodle). This excellent video from Prof. Bill Hammack at the Univ. Of Illinois, explains all the ingenuity behind the beverage can design and how it evolved throughout the century. A true engineering marvel!



A first process selection analysis... (exercise in class)

Laser manufacturing of metals versus metal forming methods: first ***qualitative*** *discussion about process selections*

Laser manufacturing of metals

Pros

- \+ No tooling
- \+ Flexible (can be adapted to a new design without adding cost)
- \+ Depending on the laser used, may not induce any side effects or may induce just limited effects
- \+ Can apply to any metals, ductile or not…
- \+ Can produce smaller features

Cons

- – In general, low-production yield **(one part at a time)**
- – **Contouring essentially**
- – May not scale favorably with part dimensions (e.g. laser power needed, complexity, etc.)
- – Does not apply to embossing or deep-drawing
- – Folding cannot be easily done (although not impossible)

Metal forming

Pros

- \+ High-production yield (high throughput)
- \+ Multiple sequential operations
- \+ Folding, bending, embossing, deep-drawing

Cons

- – High tooling costs **(typically >20kCHF per tool)**
- – Affects the mechanical properties (hardening)
- – Does not apply well to all metal (ductility level)
- – Minimum feature sizes is governed by the tool size and its manufacturing precision
- – A new design of a part, requires a new tool (method we adapted to large production volume)

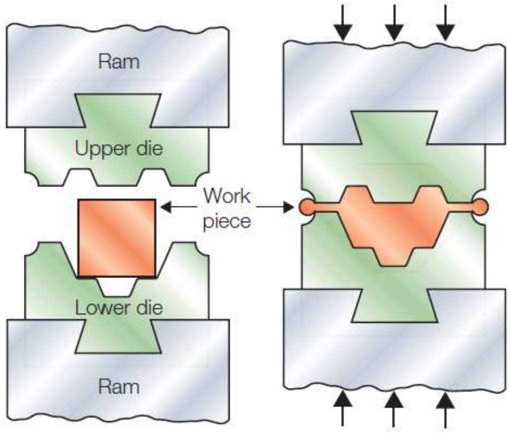
As we have now seen two types of processes that can be applied on similar materials, it is worth drawing comparisons between the two.

This exercise is useful for training our sense of critical thinking in choosing the most appropriate process for a given manufacturing problem.

Doing so, the table above list qualitative pros & cons between laser-manufacturing applied to metals and metal forming.

We encourage you to redo this exercise, each time you are confronted with a new manufacturing process; that is to say, to benchmark it with another process you are aware of, and that could be applied to similar manufacturing problems.

Forging



Forging temperature for various alloys.

Metal	°C
Aluminum alloys	400–450
Copper alloys	625–950
Nickel alloys	870–1230
Alloy steels	925–1260
Titanium alloys	750–795

See the course MSE 215 in 2nd year for more details.

- Illustrative videos:

https://youtu.be/-w7E88zox6w https://youtu.be/6jQW2I3loX4

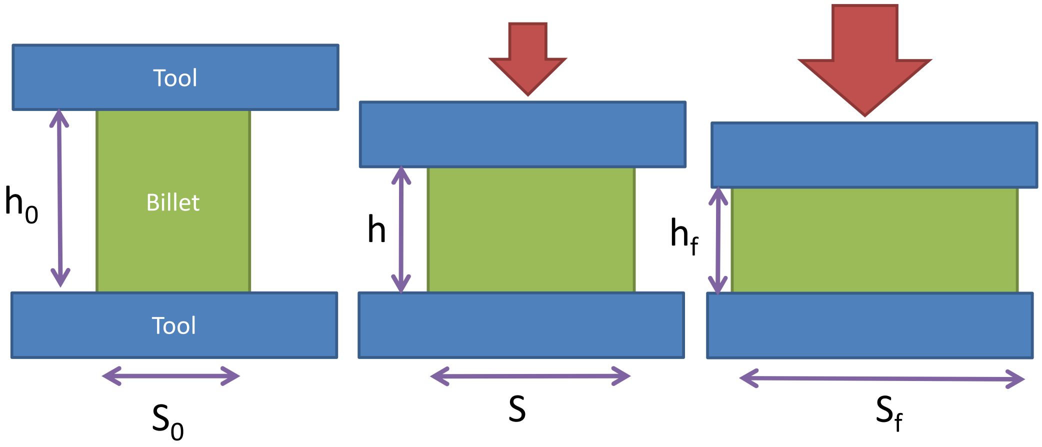
Forging belongs to the process family of metal forming.

It consists in pressing a metal blank in between two dies to force it to take the shape of the dies. It can be done in a hot or cold state. In the table above, typical forging temperature are shown for common metals.

In this course, although we mention this process for completeness, we will not go in details as the process was studied in another class. The process is also more adapted to large scale parts, and hence not much used in the context of microengineering.

Theoretical case (no friction)

$$F^{\mu=0} = \ldots$$



(using Ludwik's model)

In practice, forging consists applying a force beyond so that the material is deformed into its plastic domain.

The force increases as the contact surface increases and as the piece of metal is put into shape. If we assume that there is no friction between the object and the die, then the force can be calculated based on the contact surfaces and based on the plastic properties of the metal, for instance using Ludwik's model.

Pressure builds up during forging...

Pressure profile for a cylinder of width w and thickness h:

$$p(x)=\sigma_y e^{\frac{2\mu}{h}(w-x)}$$

Friction coefficient

Width

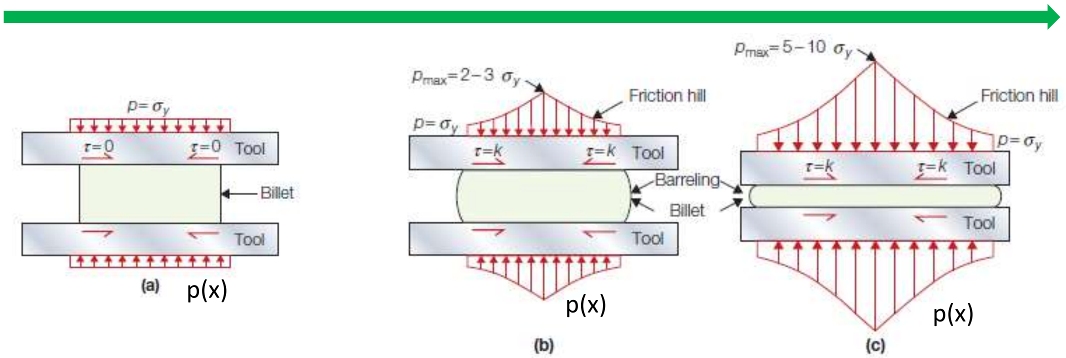
Thickness

Elastic limit (depends on temperature)

Depends on the aspect Ratio w/h

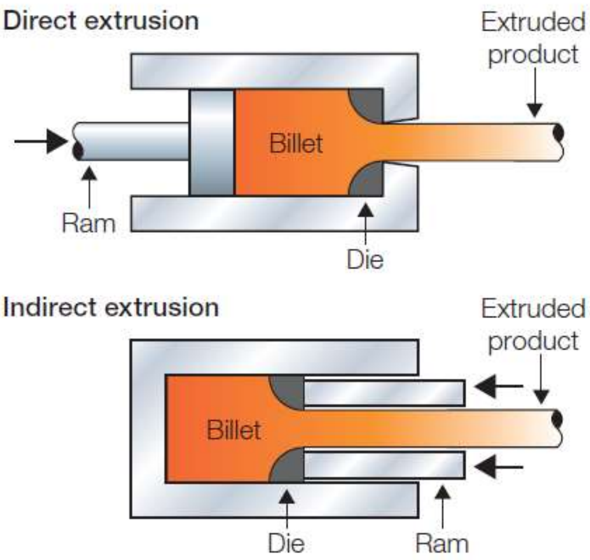
(x=0, center of the cylinder)

Evolution of the pressure profile during forging operation



In practice, friction is present, which means that the uniform stress distribution at the beginning becomes more complex as the deformation starts, taking a typical pyramid-like shape, and causing the material to form a 'barrel-like' geometry on the sides.

Extrusion ('Extrusion')



We will discuss it in the lecture related to casting/injection molding

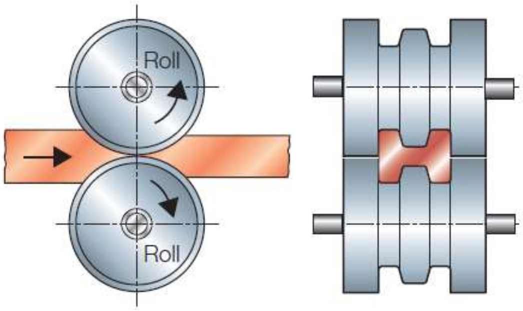
Note: we will study this process in the case of plastics. (see next lectures)

Another metal forming process is **extrusion**. As this process will be further studied in another lecture, here we will not go into details.

The general principle is to push a had metals through a die to form an elongated extruded product.

Although not identical, as we will see later on, extrusion of metals share similarities with plastics extrusion.

Rolling (‘Laminage’)

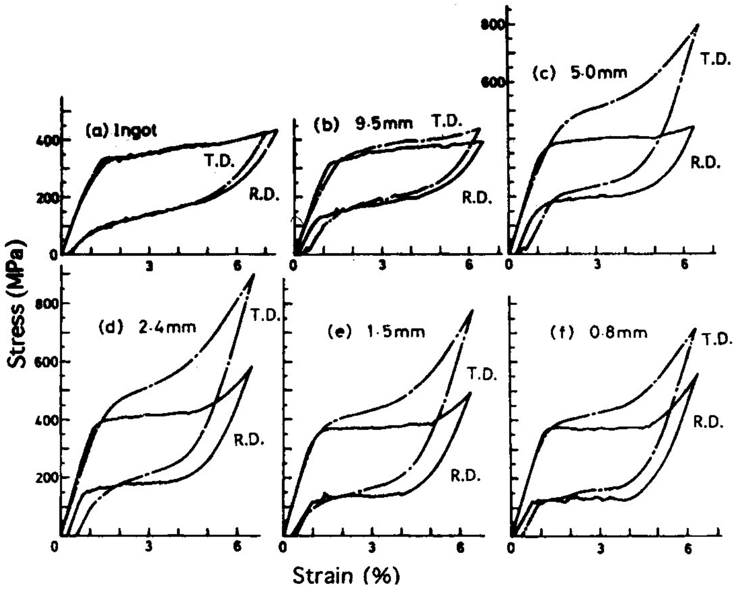


- Rolling / Illustrative videos
  - Roll forming: https://youtu.be/k6iODHla6qY
  - Hot rolling: https://youtu.be/1rR7pK45SZU

See also the course MSE 215 in 2nd year for more details on this topic.

Like forging, a common process for forming long metal profiles is the rolling process. There, the principle is to press a profile into two rollers that can be shaped or not, to create an elongated profile with a particular cross-section.

Rolling direction influences mechanical behavior…



Example in Ni-Ti superelastic Alloys

TD: Transverse direction
RD: Rolling direction

Rolling direction shows better ‘superelastic behavior’

(Source: J. van Humbeeck, Katholieke Univ. Leuven)

Due to the geometry imposed by the rolling process, the metal tends to acquire a particular texture and orientation-dependent mechanical properties.

Here, this point is illustrated for a shape memory alloys. It shows the mechanical behavior (‘superelastic’ tensile test curves characteristics of shape memory alloys) for a strip of metal taken from the transverse and rolling direction of a metal sheet.

For thin metal strips, this anisotropic effect can be pronounced and results from the geometry of the forming process and the severe deformation applied.

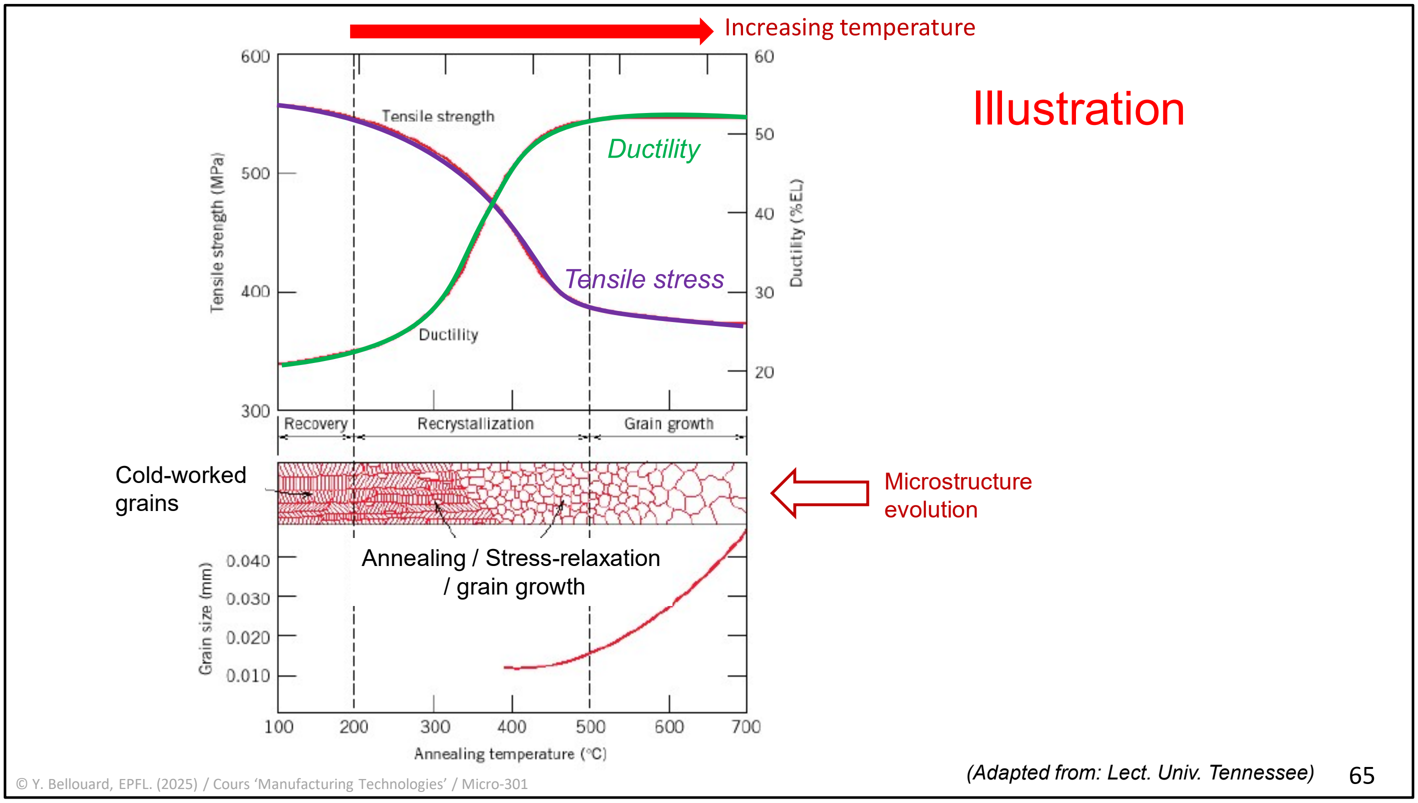
Recrystallization

- **Objective:** recover material properties after *severe* deformation (reduces the density of dislocations)
- Typically done at a fraction of the melting temperature (between 0.3 to 0.7 of the melting temperature)
- Tuning of the material mechanical properties

The last point brings an opportunity to discuss how thermomechanical treatments can be used to recover or tune mechanical properties of metal parts that have been subjected to severe deformation, as it happens in forming process.

Among these thermomechanical treatments are the recrystallisation processes.

These thermal processes, usually done at a fraction of the melting temperature of the metal, are used to recover the crystalline structure of the grains by restoring its structure and eliminating defects, such as dislocations and/or promoting grain growth.



Illustration

(Adapted from: Lect. Univ. Tennessee)

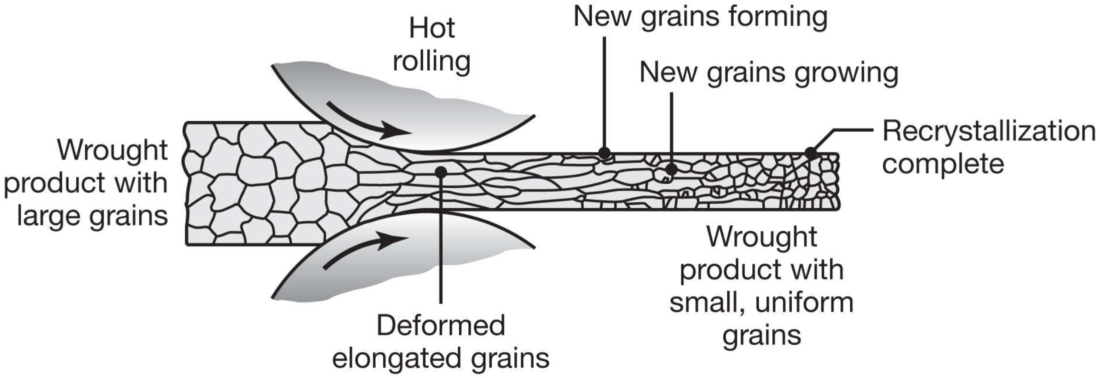
Considering our previous discussions on the role of the grain size on mechanical properties, one can see that recrystallization and strain hardening can work against one another.

Let us consider the example above. A work-hardened metal will have tiny grains and hence is likely to have a higher tensile strength, but at the expense of a reduced ductile behavior.

Performing recrystallization will cause the grain to reform into larger ones, dislocations to disappear, and consequently, a restoring of the original ductile behavior of the metal, but this time at the expense of its tensile strength properties.

Hence, the fine tuning of mechanical properties is a subtle dosage of thermal treatments and work-hardening, to find the optimal amount of ductility and mechanical strength.

Recrystallization during ‘hot-rolling’ process



Source: Kalpakjian | Schmid, *Manufacturing Processes for Engineering Materials,* Sixth Edition, Pearson Ed.

An illustration on how a metal is being deformed during a cold-rolling process.

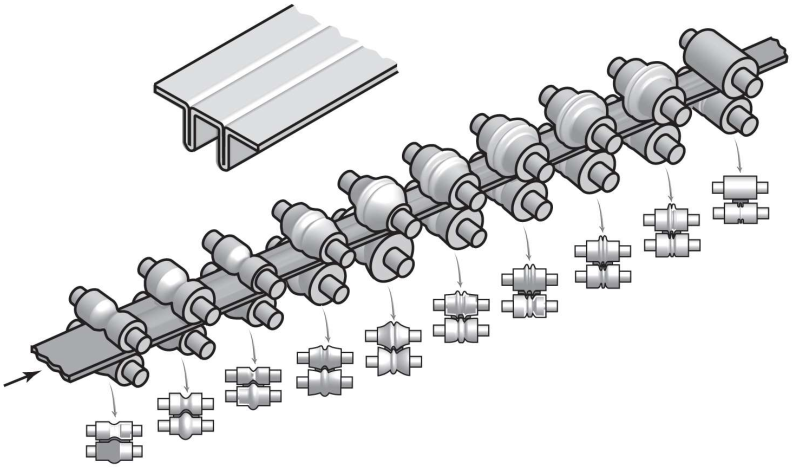
As the sheet metal is pushed through the roller, it is forced into a thinner sheet and the grain are somewhat ‘crushed’ in their thickness and stretched along the rolling direction.

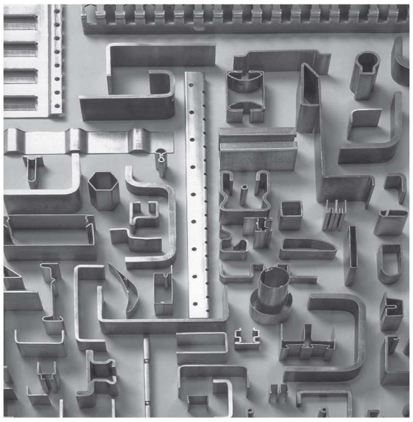
Often heat treatments are performed *in line* (i.e., as the sheet is rolled through sequential thickness reduction) to gradually restore the grain structure into a uniform structure.

While reducing a sheet metals into thinner and thinner layers through successive rolling passes, multiple intermediate recrystallisation steps are required to prevent the material to fracture (‘explode’) as there is a maximum amount of deformation it can withstand per rolling pass.

Recrystallisation in this case can be seen as an intermediate ‘reset’ of the mechanical structure, so that the material can be further deformed and so that the process of thickness reduction can be continued.

Example of continuous roll-forming profiles

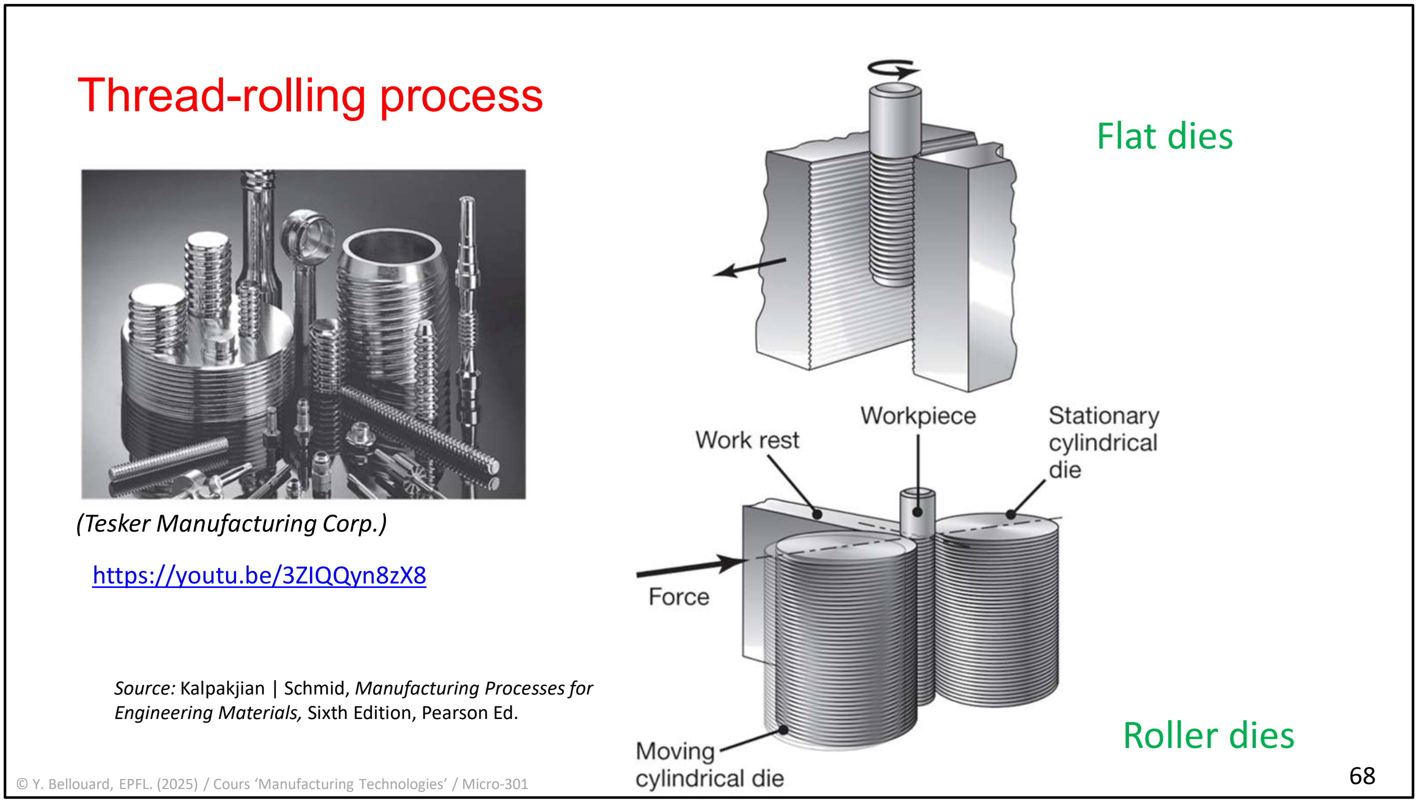




Source: Kalpakjian | Schmid, *Manufacturing Processes for Engineering Materials,* Sixth Edition, Pearson Ed.

Illustrative video:
https://youtu.be/k6iODHla6qY?si=A8_AT3TYYkQqGWBs

Continuous rolling process are used as means to form complex continuous metal profile by passing the metals through various and sequential rollers, each of which produces a dedicated folding operation.



Thread-rolling process

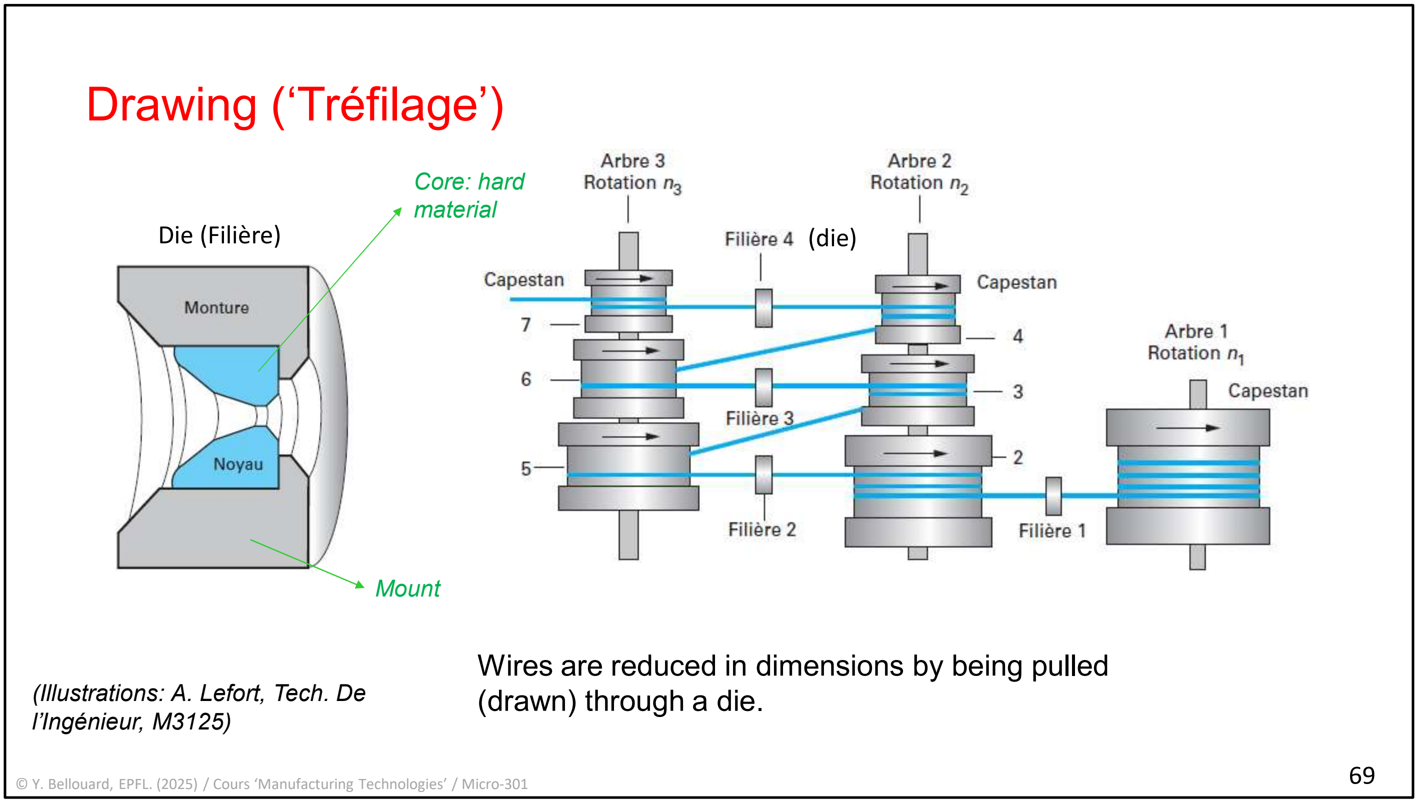
(Tesker Manufacturing Corp.)

https://youtu.be/3ZIQQyn8zX8

Source: Kalpakjian | Schmid, *Manufacturing Processes for Engineering Materials,* Sixth Edition, Pearson Ed.

Another interesting process used to produce threaded element such as screws consists of using flat or cylindrical dies with preformed grooves.

This process is used to produce screws in large quantities at a high production rate and yield.



Drawing ('Tréfilage')

Wires are reduced in dimensions by being pulled (drawn) through a die.

(Illustrations: A. Lefort, Tech. De l'Ingénieur, M3125)

Metal wires are formed following a similar process than rolling, except that this time a cylindrical profile is gradually reduced by passing it through dies of smaller and smaller diameters. The dies are usually made of hard materials capable of sustaining high stress and high friction temperature.

Wire-drawing are continuous processes for forming wires of various diameters. Just like strips of metals produced through rolling processes, wire-drawing often requires intermediate heat treatment so that the metal can sustain further deformation as its diameters is sequentially reduced until it reaches its final diameter.

Wrap-up: things to remember

- Various methods to shape metals (most common)
  - Bending
  - Drawing / cutting
  - Cold-rolling / cold-drawing and hot-rolling / hot-drawing
  - Progressive-die methods
- Mechanical analysis: how to do it
- Importance / role of heat treatments

This complete our overview of processes and methods for metal forming. These processes are essential in manufacturing and are used to manufacture many parts or objects surrounding us.

The key things to remember is the generic methods sustaining metal forming (as listed above), how it can be analyzed mechanically as well as the role and importance of methods derived from materials science to recover and tune essential engineering properties of metals.

‘Lexique manufacturing’

English (UK) > French

- Blanking: *Poinçonnage*
- Embossing: *Emboutissage*
- Deep-drawing: *Emboutissage profond*
- Bending: *Flexion, pliage*
- Spring-back force / strain: *Force d’élasticité de rappel / deformation de retour*
- (Thread) drawing: *Tréfilage*
- Rolling: *Laminage* / Cold-rolling: *Laminage à froid* / Hot-rolling: *Laminage à chaud*
- Forging: *Mise en forme à chaud*
- Thread-rolling: *Filetage par roulage*
- Stamping: *Etampage*
- Progressive die-stamping: *Etampe à suivre*