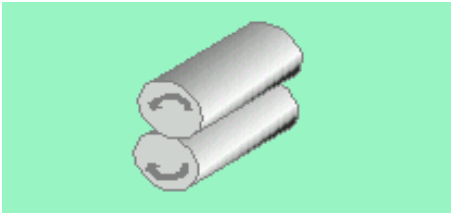
ME 4563

Introduction to Manufacturing Processes

College of Engineering
Arkansas State University

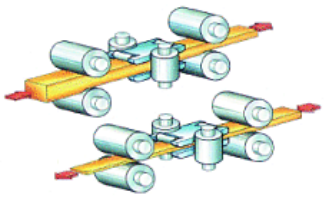
Bulk Deformation

Rolling



What is Rolling ?

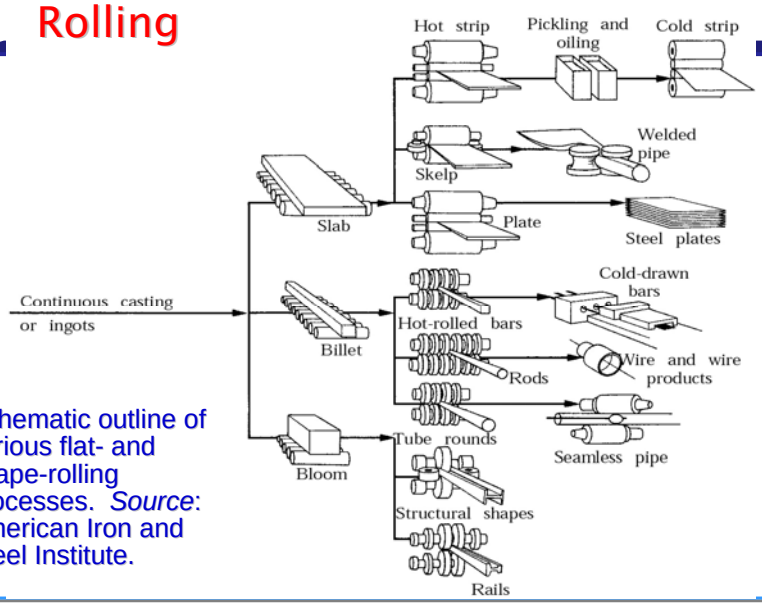
- A process of reducing the thickness (or changing the cross-section of long work-piece
- By applying compressive forces through a set of rolls



Some Rolling Facts …

- Process developed in late 1500's
- Accounts for over 90% of all metals produced by metalworking process by volume
- Various cross-sectional shapes are achieved
- Major metal that is rolled is Steel, followed by Aluminum
- Can be carried out Hot or Cold
- Machinery for Rolling (called "Mills") have a variety of configurations
- Several parameters to be considered in practice, in the design and selection of machines

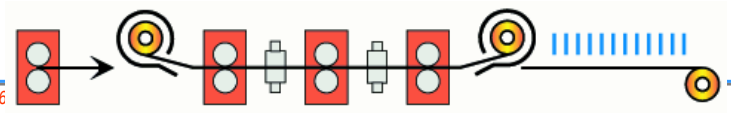
Rolling



Schematic outline of various flat- and shape-rolling processes. *Source*: American Iron and Steel Institute.

Rolling – Products include

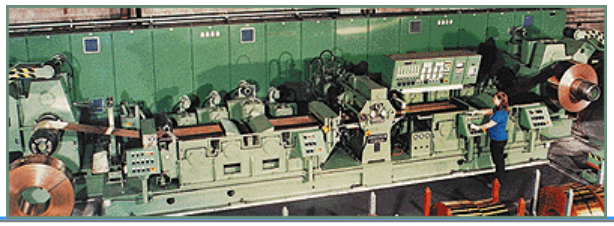
- Plates
- Sheets
- Rods
- Foil
- Pipes and tubes
- Shape rolled products such as channel, I, L, T, etc.
- Other structural shapes also made



Rolling

Major Metals that are Rolled include:

- Steel
- Aluminum
- Others like Copper, Brass, Lead, etc.
- Special applications – Titanium and other exotic metals



Rolling

Direct Applications - where rolled plates/sheets are used

- Aircraft bodies
- Ship hulls
- Reactor vessel walls
- Boilers
- Bridges
- Tanks, etc.

Indirect Applications - where rolled plates/sheets are used after further processing

- Locomotives
- Automobiles
- Appliances
- Food/Beverage containers
- Office equipment,
- Construction, etc. etc.

Rolling

Classifications of Rolling Material

Rolling material is separated into classifications based on the material's cross-sectional dimensions

	Cross-Section	Thickness	Width
Bloom	Square	> 6 in.	< 2 * thickness
Billet	Square or Circular	< 6 in.	< 2 * thickness
Slab	Rectangular		> 2 * thickness
Plate		0.25 in. < x < 12 in.	
Sheets		0.008 in. < x < 0.25 in.	
Foil		<0.008 in.	

Rolling

What kind of Thickness are we talking about ?

When Manufactured:

Rolled Plates: normally > 6mm

Rolled Sheets: normally < 6mm

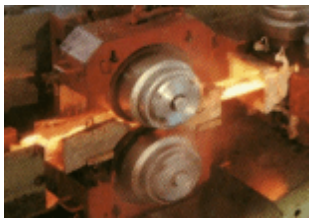
And the range of applications …

- Aircraft Body: 1 – 2mm thick
- Aluminum beverage cans: 0.1 – 0.28mm thick
- Aluminum Foil: 0.008mm thick (wrapping)

Rolling

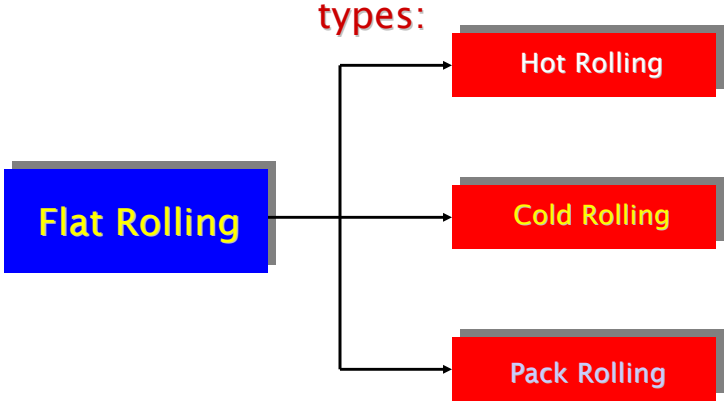
Two Major types of rolling processes -

- Flat rolling – to produce Plates and Sheets of metal
- Profile (or Shape) rolling – to produce all other possible shapes



Rolling

Flat Rolling Process can be divided into THREE major types:



Rolling

Flat Rolling Process

Hot Rolling → Converts a cast structure into a wrought structure; rolled above the re-crystallization temperature
(process in which new equiaxed / strain free grains are formed, replacing old grains)

Cold Rolling → Carried out a room temperature; better finish, mechanical properties

Pack Rolling → Two or more layers of metals are rolled together; improves productivity (Al foil)

Rolling

Other Flat Rolling Process

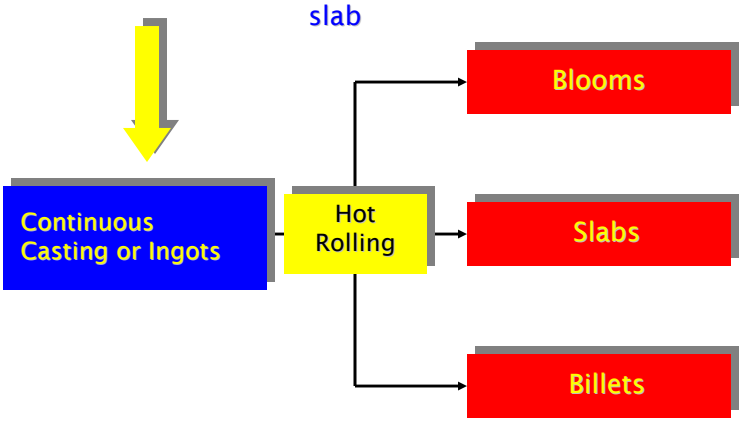
Temper Rolling → Sheets subject to a final pass – strain in the sheets are removed (sheets undergo yield point elongation during rolling); also called *skin pass; 0.5 to 1.5% reduction in thickness*

Leveling → To improve flatness. Sheets may not be sufficiently flat due to various reasons such as roll gap and process parameters

Rolling

Flat Rolling Process

Preliminary Rolling :: Initial breakdown of Ingot or cast slab



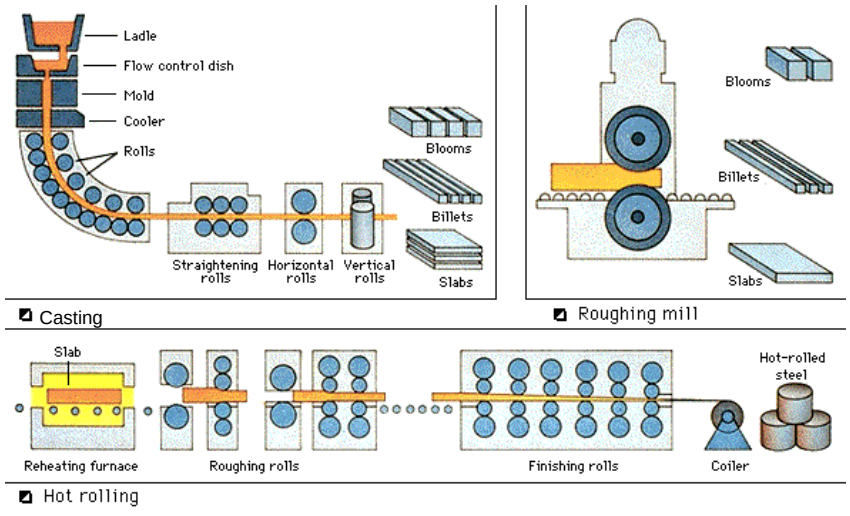
Rolling

Flat Rolling Process

Preliminary Rolling ::

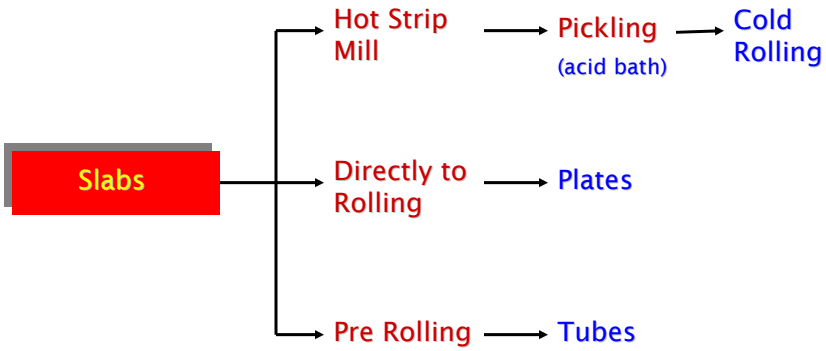
- **Blooms** → About 6” square in cross section; various lengths
- **Slabs** → Thinner rectangular cross section; various lengths (thinner version of a bloom)
- **Billets** → Smaller square cross sections; various lengths

Continuous Flat Rolling Process – A Schematic



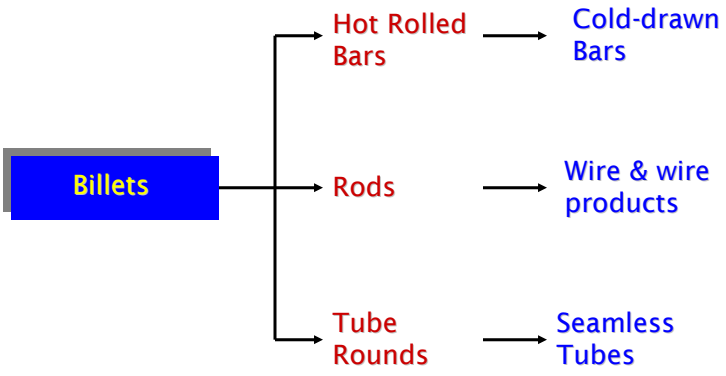
Rolling

Flat Rolling Process - Products



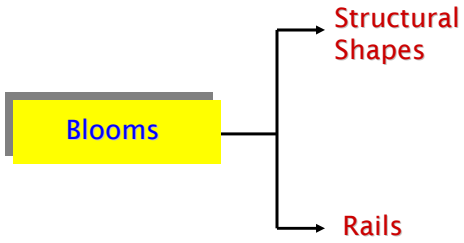
Rolling

Flat Rolling Process - Products



Rolling

Flat Rolling Process - Products



Rolling

Other Rolling Operations

Consists of these major categories:

- Shape Rolling
- Ring Rolling
- Thread Rolling
- Rotary Tube Piercing
- Tube Rolling

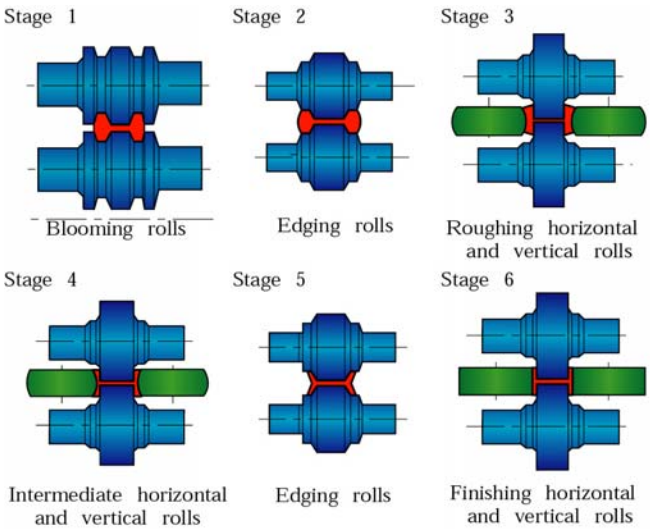
Rolling

Other Rolling Operations

A. Shape Rolling

- Raw materials is usually the Bloom
- Straight structural shapes such as bars of various cross sections, channel sections, I-beams, and rails
- Rolled by passing the stock through a number of sets of rolls specially designed for these applications
- Designing the roll systems for this application takes experience and care, as material failure is fairly frequent in case of poor designs

Shape Rolling

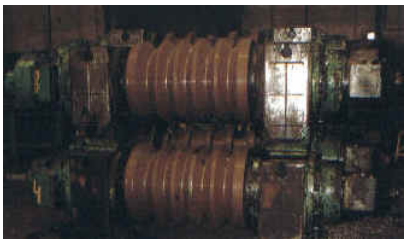


Stages in the shape rolling of an H-section part.

Various other structural sections, such as channels and I-beams, are also rolled by this kind of process.

Shape Rolling

A. Shape Rolling



Shape Rolling

A. Shape Rolling

Rolling out an angular section

Shape Rolling

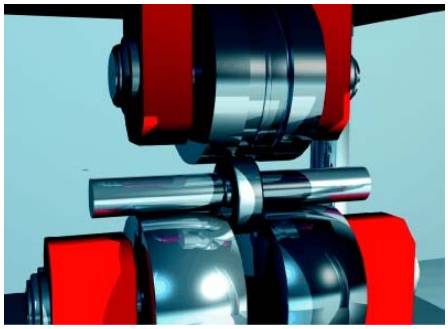
A. Shape Rolling

Rolling out a V-Section

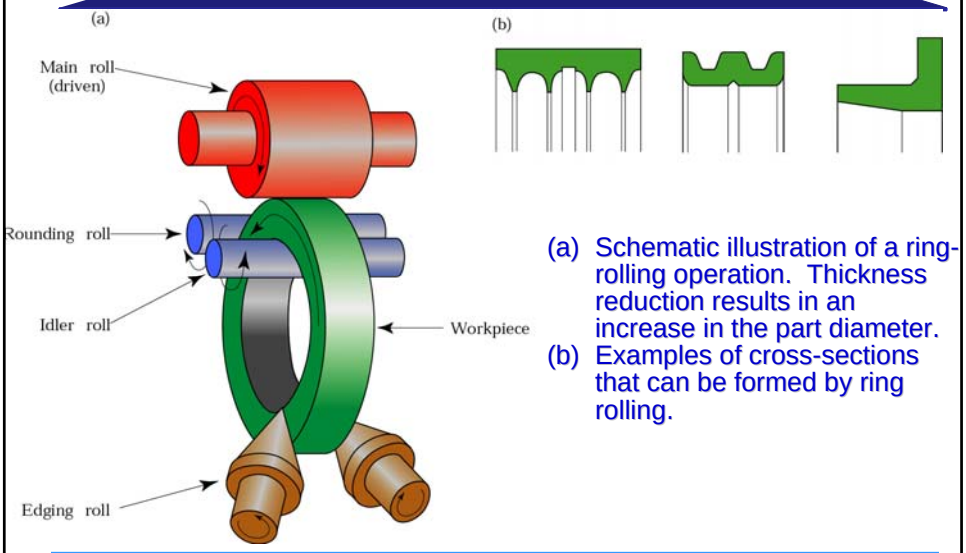
Rolling

B. Ring Rolling

- Smaller diameter thick ring is expended into a larger diameter thinner ring
- System consists of two rolls – one which performs the rolling and the other to support and guide
- With each rotation, the thickness is reduced as the rings come closer together



Ring Rolling



(a) Schematic illustration of a ring-rolling operation. Thickness reduction results in an increase in the part diameter.
(b) Examples of cross-sections that can be formed by ring rolling.

Ring Rolling

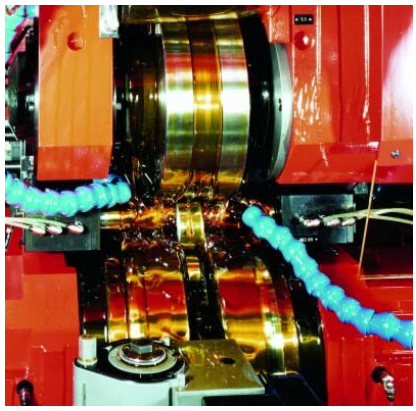
B. Ring Rolling

- Variety of cross sections can be ring-rolled with shaped rolls
- Short production runs, material savings, closer tolerances, favorable grain flow
- Rockets, turbines, gearwheel rims, bearing races, etc.

Rolling

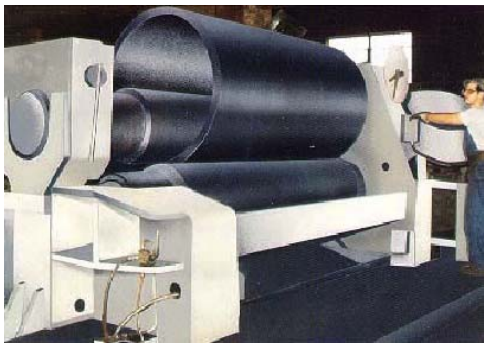
B. Ring Rolling

Ring Rolling Machine



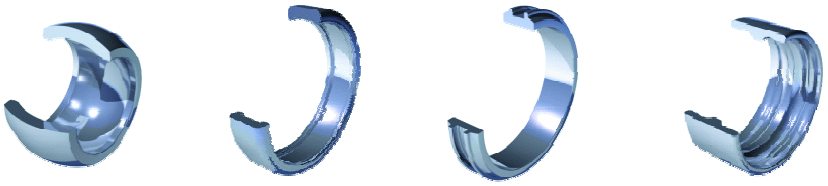
Rolling

B. Ring Rolling



Rolling

B. Ring Rolling - Examples

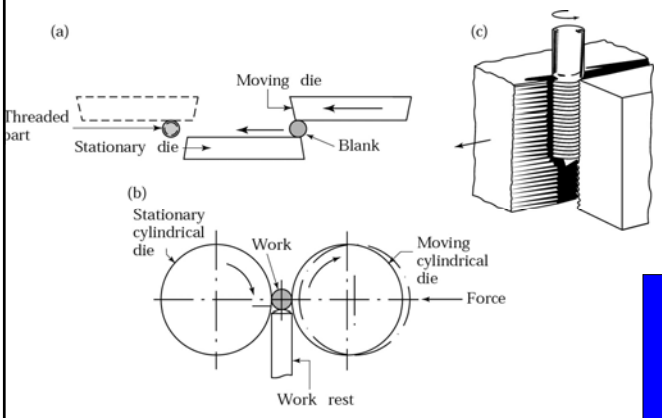


Thread Rolling

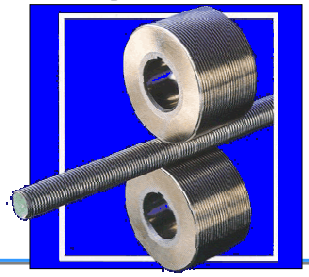
C. Thread Rolling

- Threads or gear teeth formed on round rods by rolling
- Flat reciprocating dies and round rotating dies are used
- Good for external threads - High production rate for screws, bolts
- No loss of material – smaller diameter rods to start with
- Greater strength due to cold working, as compared to a regular thread cutting process
- Ductility of material is crucial as well as good lubrication in the process
- Typically faster - at three times the cutting process

Thread Rolling

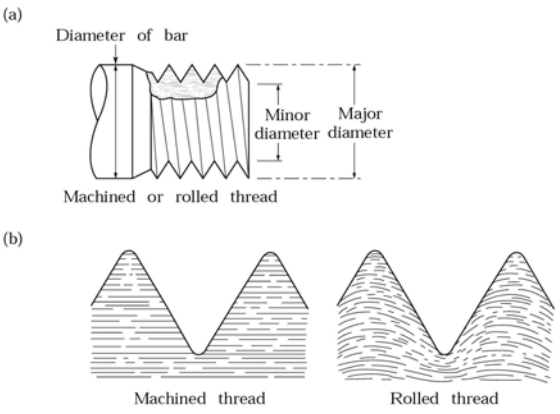


Thread-rolling processes:
(a) and (c) reciprocating flat dies;
(b) two-roller dies. Threaded fasteners, such as bolts, are made economically by these processes, at high rates of production.



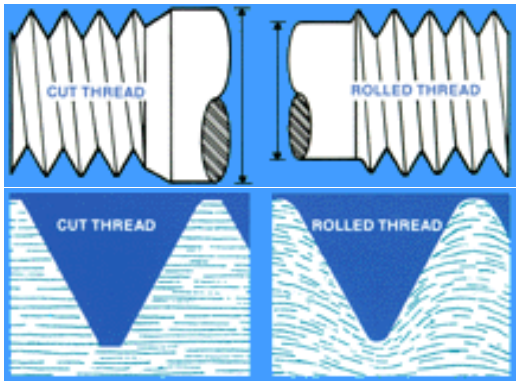
Thread Rolling

(a) Features of a machined or rolled thread.
(b) Grain flow in machined and rolled threads. Unlike machining, which cuts through the grains of the metal, the rolling of threads causes improved strength, because of cold working and favorable grain flow.



Thread Rolling

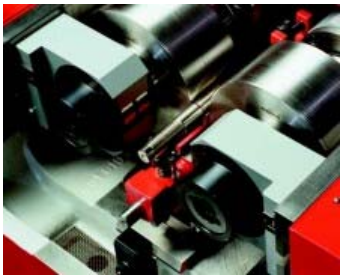
C. Thread Rolling – Material is not wasted

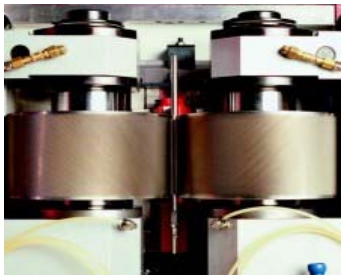


Cut Thread Rolled Thread

Thread Rolling

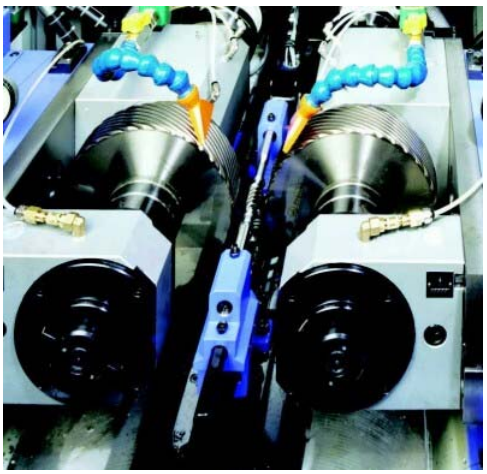
C. Thread Rolling





Thread Rolling

C. Thread Rolling



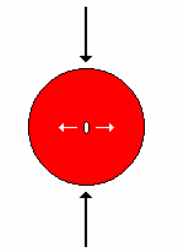
Thread Rolling

Examples

Rolling

D. Rotary Tube Piercing

- A hot-working process – used to make long thick wall seamless tubing
- When a round bar is subject to radial compression tensile stress develops in the center of the rod



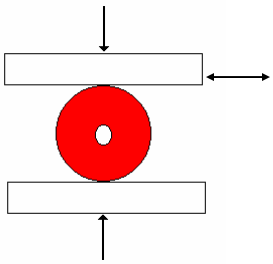
- Can be demonstrated using a round eraser and rolling it on the table !

Rolling

D. Rotary Tube Piercing

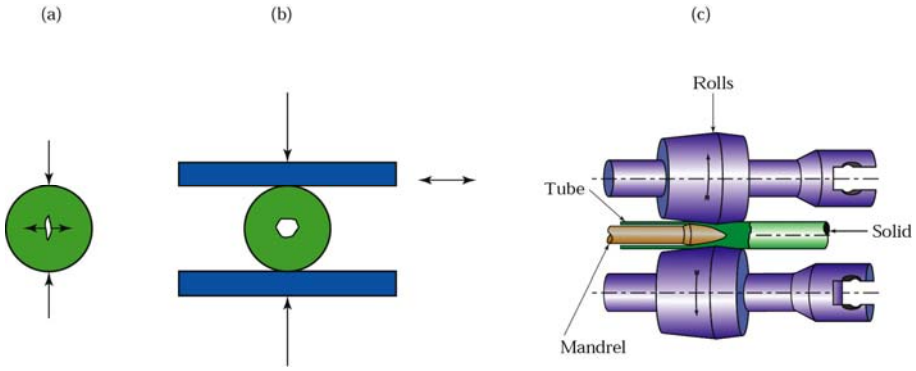
- When subject to cyclic compressive stresses a cavity begins to form in the center
- By means of piercing this hole with a mandrel of required diameter, the hole size is expanded

- Special roll arrangement with the mandrel are used
- High quality defect free bars must be used for this process



Rolling

Rotary Tube Piercing – A Schematic

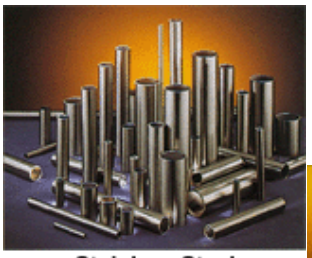


Rotary Tube piercing is also called the "Mannesmann process"

Rolls are normally arranged in a skewed manner (axes at an angle)

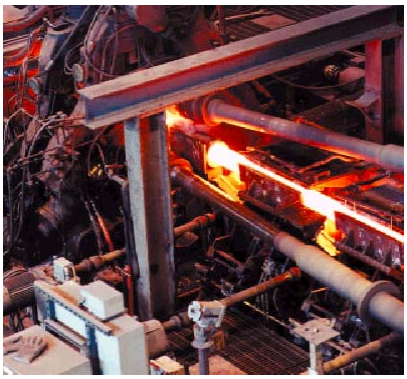
Rolling

Rotary Tube Piercing



Stainless Steel
Seamless
Welded

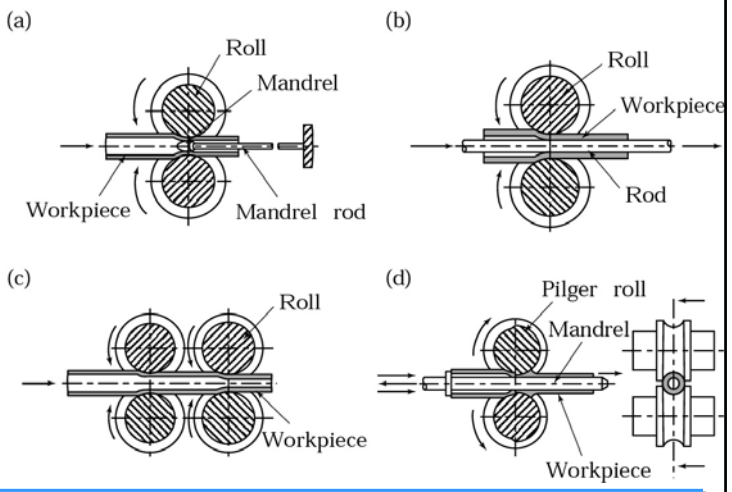
Carbon & Alloy Steel
Seamless
Welded



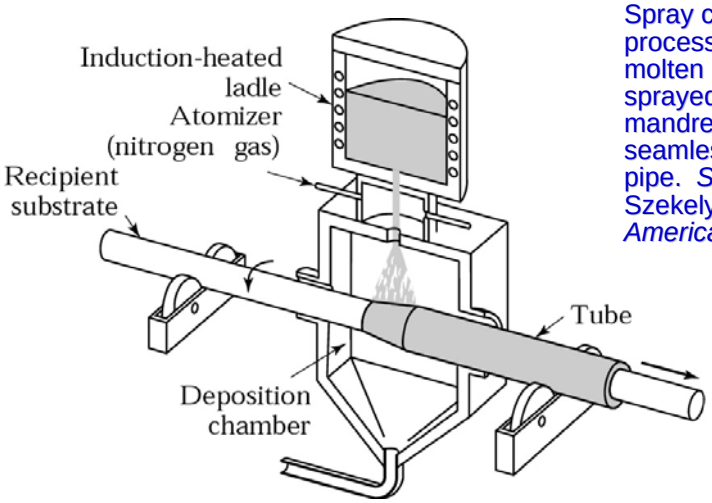
Rolling

E. Tube Rolling

Schematic illustration of various tube-rolling processes:
(a) with fixed mandrel;
(b) with moving mandrel;
(c) without mandrel; and
(d) pilger rolling over a mandrel and a pair of shaped rolls.



Rolling – Spray Casting



Spray casting (Osprey process), in which molten metal is sprayed over a rotating mandrel to produce seamless tubing and pipe. *Source*: J. Szekely, *Scientific American*, July 1987.

Rolling Mills

- Several types of Rolling mills & equipment are built, using diverse rolls arrangement
- Equipment for Hot and Cold rolling is essentially the same, except the process parameters, roll materials, lubricants and cooling system
- Very capital intensive
- Highly automated

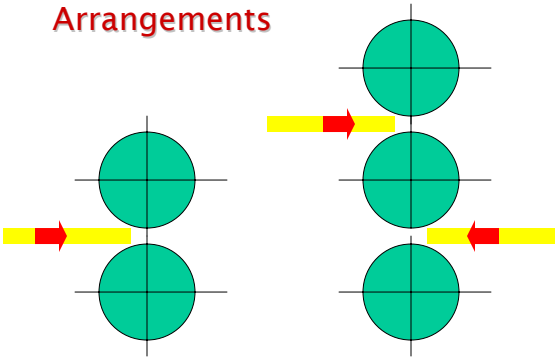
Rolling Mill

Rolling Mills

Rolls in a Semi-continuous hot strip mill

Rolling Mills

Roll Arrangements



Two-High Mill

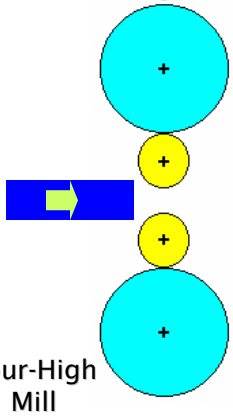
Three-High Mill

Two- and Three-high Mills

- Used in hot-rolling for initial breakdown passes on cast ingots or in continuous casting process
- Three-high reversing mill used as a two stage rolling process

Rolling Mills

Roll Arrangements



Four-High Mill

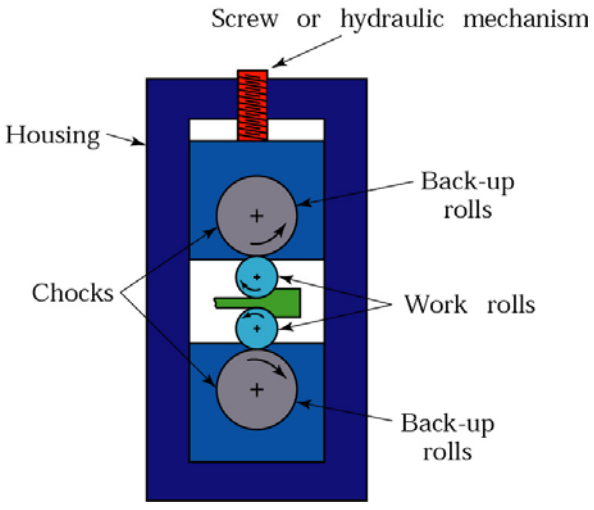
Four-high Mills

- Based on principle that smaller rolls lower roll forces and power, as well as spreading of sheets; easily replaced when broken or worn
- Drawbacks – small rolls deflect more; have to be supported by other rolls as in the four-high and cluster arrangements
- Cluster rolls (Sendzimir) most suited for cold rolling

Rolling Mills

Schematic illustration of a four-high rolling-mill stand, showing its various features.

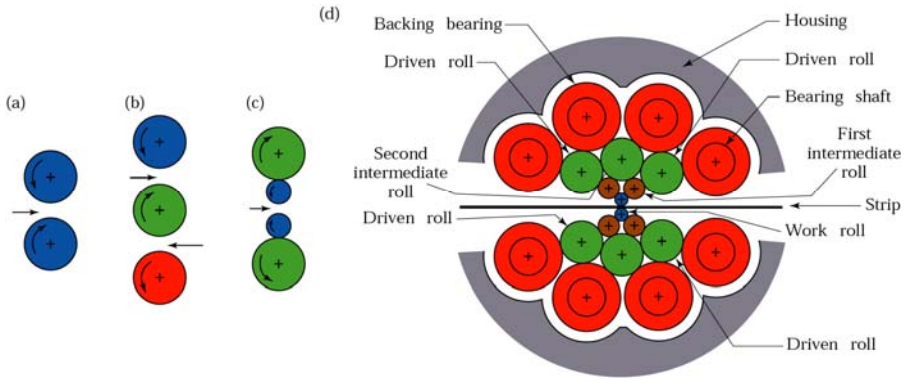
The stiffness of the housing, the rolls, and the roll bearings are all important in controlling and maintaining the thickness of the rolled strip.



Rolling Mills

Roll Arrangements

Schematic illustration of various roll arrangements: (a) two-high; (b) three- high; (c) four-high; (d) cluster (Sendzimir) mill.

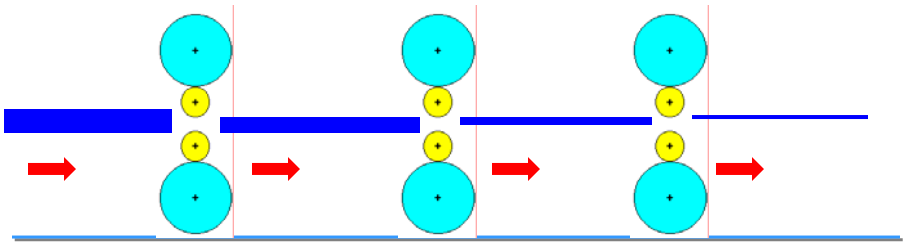


Rolling Mills

Roll Arrangements

Tandem Mills

- Strip is rolled continuously through a number of stands to smaller gauges with each pass
- Each stand has its own set of rolls and controls
- A groups of stands is called a *Train*



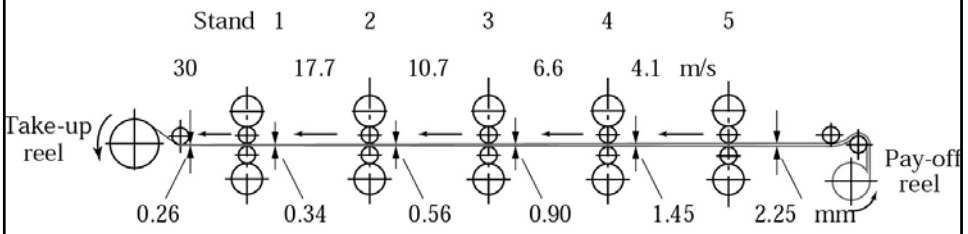
Rolling Mills

Roll Arrangements

Tandem Mills

- Dimensions at different stages

…



Rolling Mills - Rolls

- Strength and Resistance to wear
- Made of Cast iron, cast steel & forged steel.
  Tungsten carbide for smaller diameter rolls
- Forged steel among the best materials – greater strength, stiffness and toughness
- Rolls are ground to fine finish for cold rolling.
  Polished for special applications
- Rolls for hot and cold rolling are not interchangeable

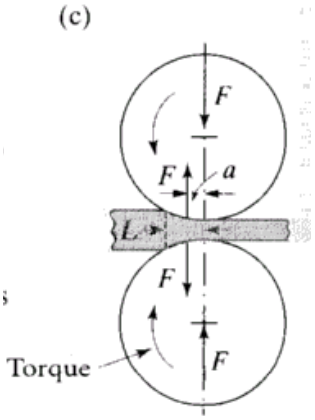
Rolling

Problems with Rolls in Practice

- Because of forces acting on them, rolls undergo geometric changes
- As a result, there are problems with the resulting rolled product

Effect of Roll Forces

- The forces result from the resistance of the material to deformation, and cause
  - Roll bending
    - Non flat material
      - Cambered sheet
      - Buckling
  - Roll flattening
    - Poor tolerances
    - Increased forces (larger contact area)



Roll Force Compensation

- Rolling forces set the energy required for the process and the size of the equipment required

- Roll Forces can be decreased by:
  - Reducing friction – use of Lubricants
  - Using smaller diameter rolls (e.g., in the Sendzimir mill)
  - Smaller reductions per pass (lesser Residual stresses)
  - Increasing the temperature (via Hot rolling)
  - Provide backup rolls (four high)
  - Camber rolls to compensate roll deflection
  - Bend rolls back

Reducing the Roll Force

- **Lowering the friction**
  - **Friction is lower for cold rolling than for hot. With effective lubricant:**

    Cold Rolling - friction = 0.2 to 0.3
    Hot Rolling - friction = 0.2 to 0.7
  - **Choose the right material for rolls**
  - **Modify the lubrication parameters (Type, Amount, Method of Application)**
- **Reduce the Roll Radius**
  - **This also lowers the energy**
  - **Reducing the roll radius shortens the length of contact**
  - **However, rolls will be more prone to deflection (see defects)**

Reducing the Roll Force

- **Use Lower Reductions**

  This may increase the number of required passes, thus requiring:

  More time
  Possibly more equipment requirements
  Possibly more energy

- **Increase the Work piece Temperature**

  This lowers the yield point

  This allow recrystallization and reduces strain hardening

- **Apply Tension**

  Either side will reduce the force

  If applied at the entrance, termed back tension

  If applied at the exit, termed front tension

Rolling Mills - Lubricants

Lubricants …

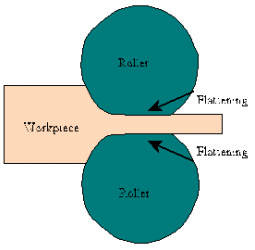
- Normally none used for rolling Ferrous alloys; Graphite may be used sometimes
- Water-based solutions are used to cool the rolls
- Non-ferrous alloys are hot-rolled with variety of lubricants such as oils and fatty acids
- Cold rolling is carried out with low-viscosity lubricants such as mineral oils, paraffin, etc.

Rolling – Vibration and Chatter

- Significant effect on product Quality and Productivity
- Chatter (self excited vibration) can occur in rolling as well as other processes (extrusion, drawing, machining, etc.)
- Related to the dynamics of the rolling action
- In Rolling – predominantly occurs in Tandem mills
  - variation in thickness, poor surface finish, high levels of scrap
  - frequencies related to the resonance as well as other natural frequencies of the system
- Controlled by process parameters: distance between roll sets, width of job, speed of rolling, increasing damping, etc.

Rolling – Problems with Rolls

Roll Flattening



- The forces of rolling will flatten the rollers elastically - similar to tires on the road surface (Roll radius, Modulus of elasticity, roll forces)
- This flattening causes an increase in the contact area
- The increased contact area causes the forces to increase
- Roll Flattening can be reduced by:
  - Using a roller material with a higher modulus of elasticity
  - Reducing the roll force

Rolling – Problems with Rolls

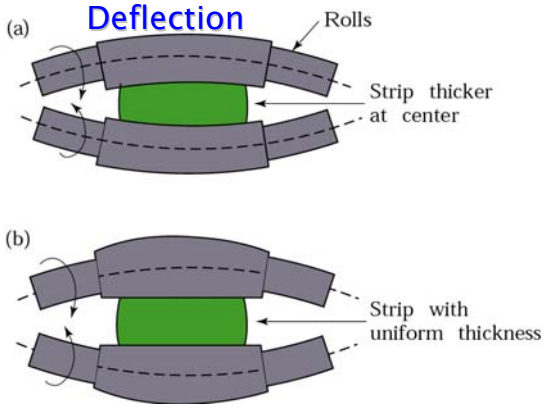
Roll Deflection

- Roll forces tend to bend the rolls: leading to a strip that is thicker at the center than at the edges
- Solution: Grind the rolls such that the diameter at the center is slightly larger than at the edges
  - This is known as giving them *CAMBER* – In practice, this would generally be around 0.25 mm or less on the radius. Camber is only correct for a
    - *given load on the roll*
    - *thickness of the strip*

    Hence normally done for a large batch, due to economic reasons

Rolling – Problems with Rolls

Roll Deflection



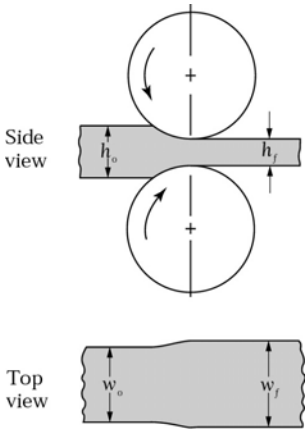
(a) Bending of straight cylindrical rolls, caused by the roll force.

(b) Bending of rolls ground with camber, producing a strip with uniform thickness.

Rolling – Problems with Rolls

Spreading

- Rolling plates sometimes causes the width to increase considerably
- This increase is called *SPREADING*
- Controlled with:
  - high width-to-thickness ratio
  - roll radius to strip thickness ratio
  - decreasing friction between rolls and material



Spreading can be observed when dough is rolled with a rolling pin.

Defects due to Rolling

Successful Rolling depends upon various factors including material properties, process variables, and lubrication

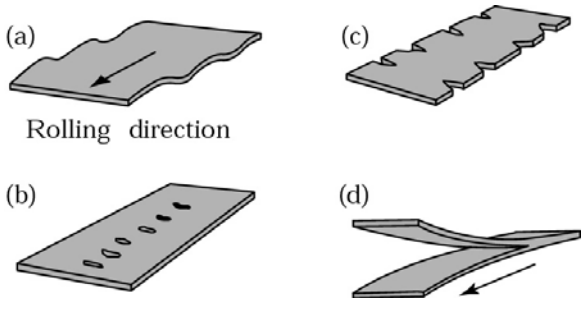
- Defects:
  - on the surface of the rolled material
  - structural defects within the rolled material
- Surface Defects:
  - inclusions and impurities in the material
  - scale, rust, dirt, roll marks, etc., caused due to prior treatment and working of the material
  - Remedy: precondition the material by cleaning it by various means

Defects due to Rolling

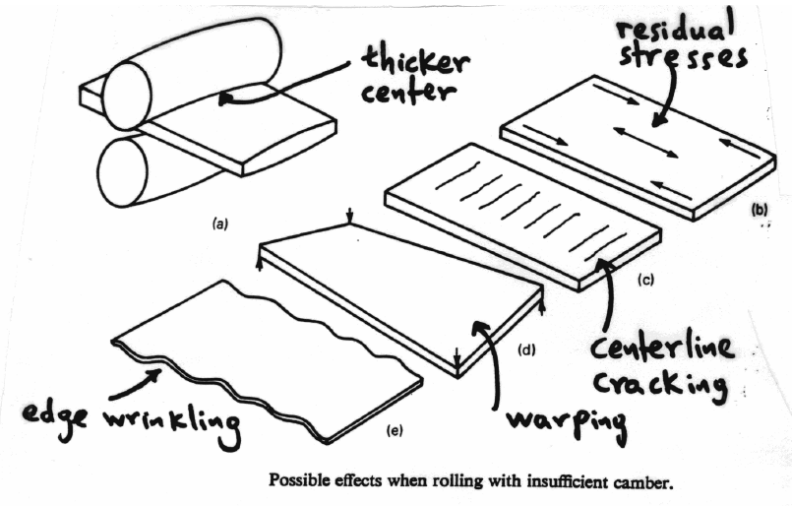
- Structural Defects: distort or affect the integrity of the rolled product
  - Wavy Edges – Edges are thinner than the center caused by bending of the rolls
    - the edges elongate more then the center and are restrained from expanding freely, they "buckle"
  - Cracks in the Rolled Product – usually caused by low ductility and barreling (in the edges & middle)
  - Alligatoring – resulting from inhomogeneous material deformation during rolling and defects in the original cast ingot itself

Defects due to Rolling

Schematic illustration of typical defects in flat rolling:
(a) wavy edges;
(b) zipper cracks in the center of the strip;
(c) edge cracks; and
(d) alligatoring.

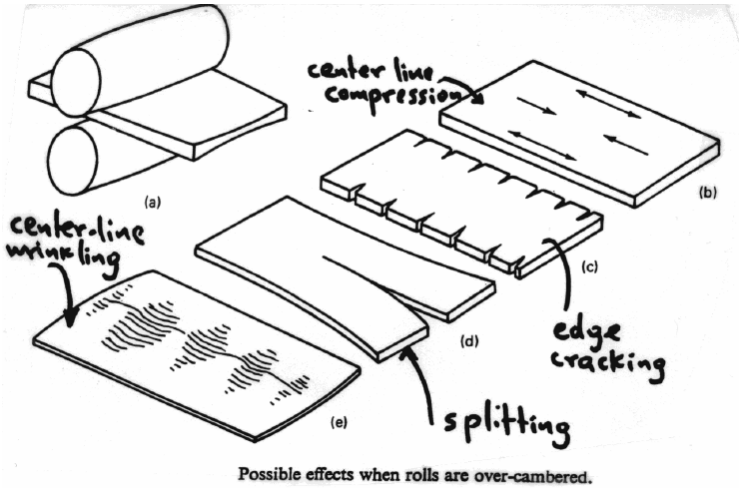


Defects due to Rolling



Possible effects when rolling with insufficient camber.

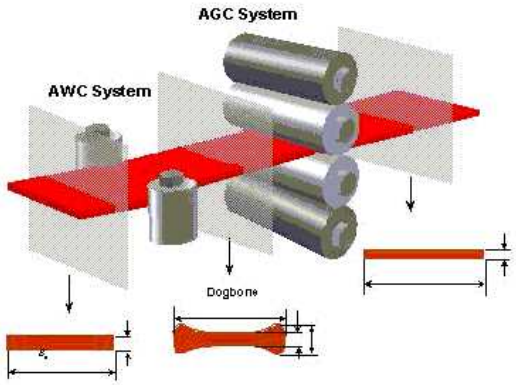
Defects due to Rolling



Possible effects when rolls are over-cambered.

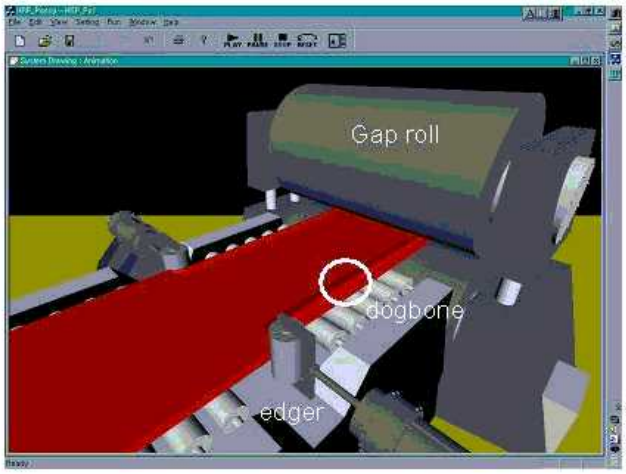
Defects due to Rolling

Taking care of wavy edges



Defects due to Rolling

Taking care of wavy edges



Hot Rolling

Hot Rolling

- Hot Rolling is done between 100 and 200 degrees F above the re-crystallization temperature for most metals
- Hot rolling gives a final product with a fine grain size and little strain hardening
- This provides increased material yield strength
- This also provides increased ductility, by breaking grain boundaries, closing internal defects and breaking inclusions

Hot Rolling

Advantages

- Stresses lower
- Forces smaller
- Power requirements less
- No work hardening
- Large deformations possible
- Breaks up the cast structure into preferable forms
- Closes porosity
- Sometimes the only way to create sheet

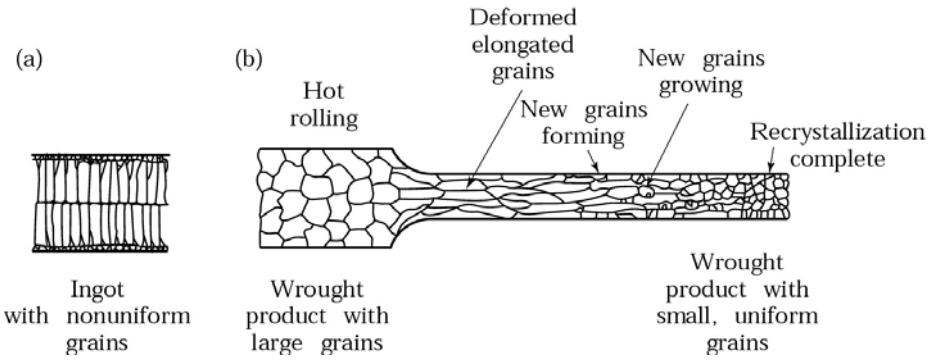
Hot Rolling

Disadvantages

- Higher friction
- Rolls need to be cooled
- Material handling difficult
- Personnel must be protected from heat

Hot Rolling

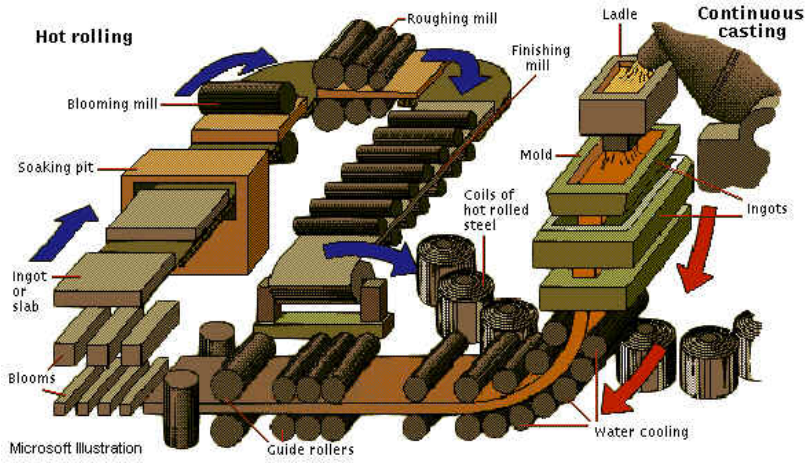
- Causes changes in the grain structure of cast or of large-grain wrought metals
- Hot rolling is an effective way to reduce grain size in metals, for improved strength and ductility



Hot Rolling – some points

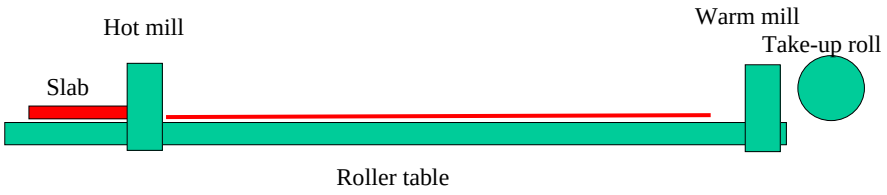
- The final product has little directionality, however:
  - If there are non-metallic inclusions, they will not recrystallize and may impart directionality
  - Alloying elements that have a high recrystalliztion temperature may cause the same effect
  - Thinner sheets will have more directional characteristics
- The final product has few residual stresses, however:
  - Non-uniform cooling can induce substantial residual stresses
  - The edges may warp due to rapid cooling, especially in more complicated shapes (I-beam, Flanges do this)
- The final surface is rougher, surface will contain difficult to remove high-temperature oxides (termed mill scale), tolerances can usually be held to 2 - 5% of the specified dimension

Casting & Hot Rolling – a schematic



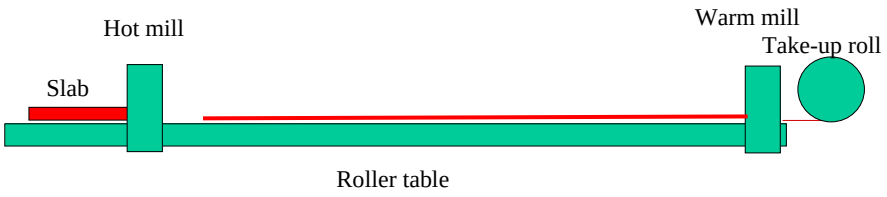
Hot Rolling Mill Design

- Basically the same as cold mills, but designed for higher temperatures and are reversible
- Typically have edging rolls to control thickness
- Often have a warm mill at the end



Hot Rolling Mill Design

- Basically the same as cold mills, but designed for higher temperatures and are reversible
- Typically have edging rolls to control thickness
- Often have a warm mill at the end



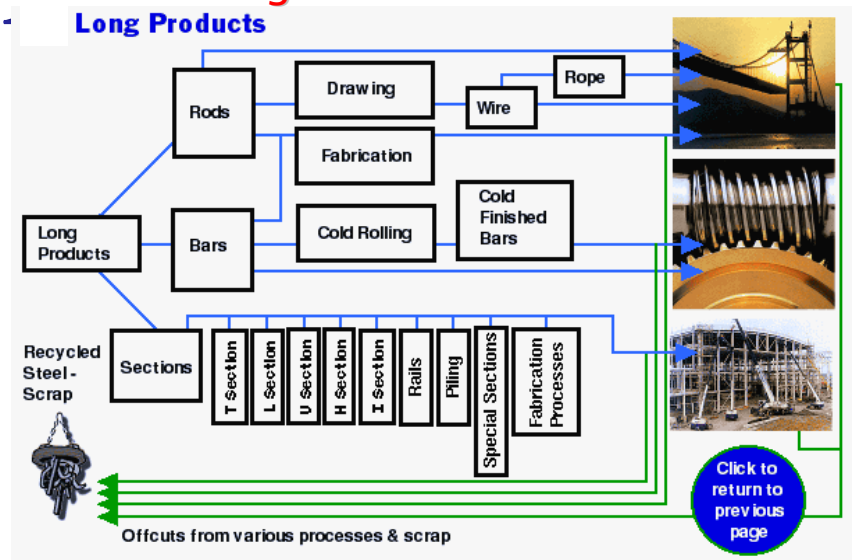
Hot Rolling Process - Example

- Start with 12in. thick slab, 20 feet long
- Hot mill converts to 2 in thick slab, 120 feet long with 11 passes (six forward and 5 reverse)
- Front end sheared off to eliminate alligatoring
- Warm mill converts this to *roll* of sheet 0.25 in thick, 960 feet long
- Rolls more easily handled by overhead cranes to transport it to cold mills than 1000 ft long slabs

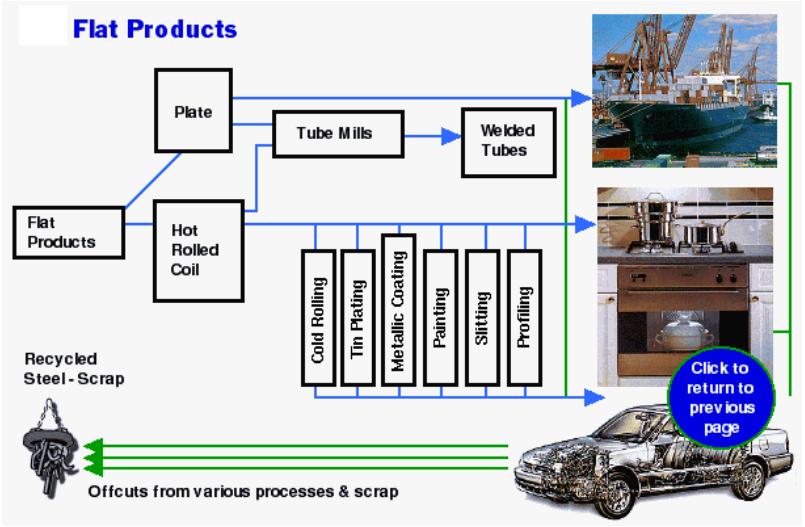
Overall Process for Sheet and Plate

- Cast ingot
- Scalp (not always)
- Reheat and homogenize (uniform)
- Hot roll in reversing mill to ~1-2 in thick
- Cut off ends (alligators)
- Warm roll to 0.1-2 in thick
- Heat treat to recrystallize (sometimes)
- Cool
- Cold roll to finish thickness
- Heat treat (where appropriate)
- Results in material which must be further worked

Hot Rolling

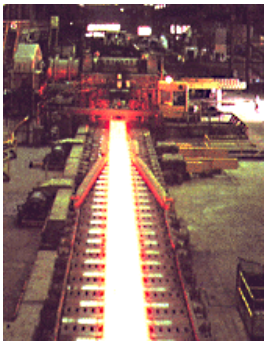


Hot Rolling



Hot Rolling

Rolling Mill



Hot Rolling

Hot Rolling

Closer Look

Hot Rolling

Continuous Steel Casting Line rolling out billets

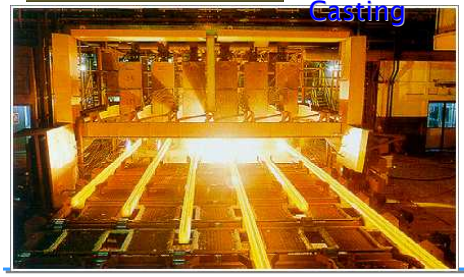
Hot Rolling

Continuous Rolling of Billets

Hot Rolling

Steel Billets

Billets Casting



Steel Slabs (from slab caster)

Hot Rolling

Hot rolled strips being coiled

Hot Rolling

Rolling of Rails

Hot Rolling

Hot Cutting the rolled Rails

Hot Rolling

Section of the Mill where rolling is taking place

Rolling – Further Processing

Profiled color-coated steel sheets

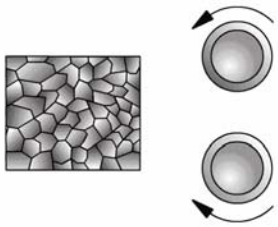
U-section long bars

Rolling – Further Processing

Wire rods in a coil

U-section long bars

Cold Rolling



Cold Rolling

Cold Rolling

- Hot rolled coil is commonly cold rolled (also known as cold reduced).
- The strip is first de-coiled (uncoiled) and then passes through a series of rolling mill stands which apply pressure to the strip and progressively reduce its thickness - down to as low as 0.15 mm.
- The strip is then recoiled.
- Cold rolling processes are also used to improve the surface quality of the steel.
- Cold rolling also has the effect of hardening steel, so cold reduced strip is subsequently annealed: a process of very carefully controlled heating and cooling to soften it

Cold Rolling

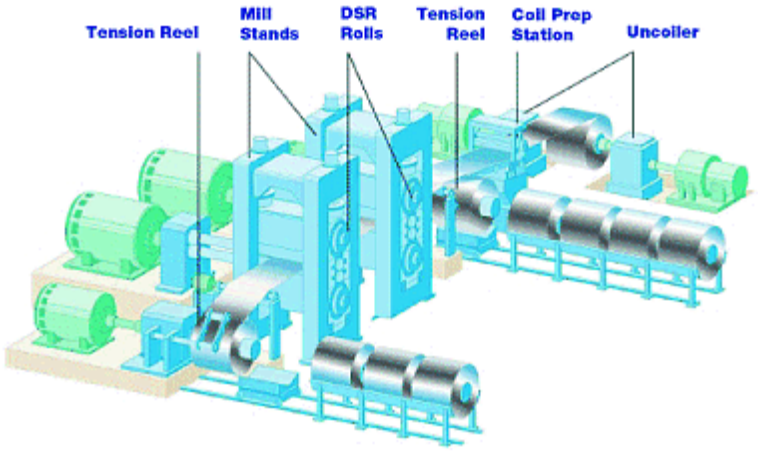
- Advantages
  - Deformations of ~ 50 to 80%
  - Work hardening increases strength
  - Excellent surface finish
  - Excellent tolerance on thickness and shape
- Disadvantages
  - High forces
  - Small reductions give rise to surface stresses and non-uniform stress distributions
  - ?

Cold Rolling Mill Design

- Input and output coils with tensioning control
- Shape meters consisting of segmented coils measuring force
- Tandem mills allow multiple reductions in one operation
- Laser inspection systems for surface finish inspection becoming popular (especially for canstock)
- Surface condition of rolls critical to maintain surface finish
- Roll bending almost essential to provide crown control

Cold Rolling

Cold Rolling - Schematic



Cold Rolling

- Cold rolled sheet can be produced in various conditions such as skin-rolled, quarter hard, half hard, full hard depending on how much cold work has been performed.
- This cold working (hardness) is often called *temper*
- In Skin Rolling, the metal is reduced by 0.5 to 1% and results in a surface that is smooth and the yield point phenomenon--excessive stretching and wrinkling in subsequent operations, is eliminated.
- This makes the metal more ductile for further forming and stretching operations

Cold Rolling

- Quarter Hard, Half Hard, Full Hard stock have higher amounts of reduction, upto 50%.
- This increases the yield point; grain orientation and material properties assume different properties along the grain orientation.
- However, while the yield point increases, ductility decreases.
- Quarter Hard material can be bent (perpendicular to the direction of rolling) on itself without fracturing. Half hard material can be bent 90°; Full hard can be bent 45°.
- Thus, these materials can be used for in applications involving great amounts of bending and deformation, without fracturing

Cold Rolling

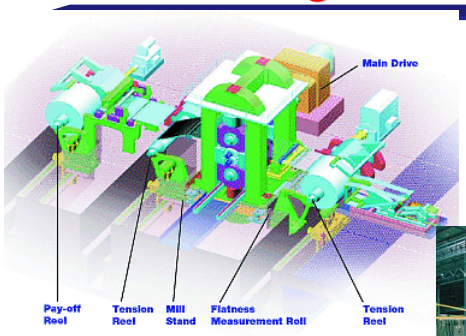
Cold Drawing

- Another form of cold processing is cold drawing
- Steel rod is dragged at pressure (drawn) through a series of dies which progressively reduce the rod's circumference to produce wire
- The drawing process substantially increases the steel's tensile strength
- Steel wires can be spun into huge ropes strong enough to support the world's largest suspension bridges

Cold Rolling

Cold rolling Mill

Cold Rolling



Cold rolling Mill

Cold Rolling

Cold Rolling

Cold Rolling

Cold rolled coil being split into narrow strips

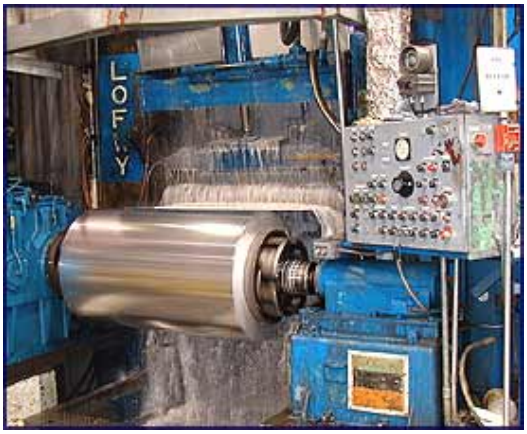
Cold rolled coils

Rolling Aluminum

Al Sheet being rolled out

Rolling Aluminum

Al Foil Roll



Independent Variables for Rolling

For a given rolling set-up:

- Roll speed
- Draft (amount of thickness reduction) or roll gap
- Billet thickness
- Billet width
- Billet material (not always allowed to select)
- Billet temperature
- Lubricant

Dependent Variables for Rolling

For a given rolling set-up:

- Roll force
- Power
- Speed of exiting strip
- Final strip temperature
- Maximum draft
- Roll strip contact length
- Sheet or plate shape

Control of Overall Properties

- Thickness
  - Roll gap which impacts roll force and hence the dimensions of the mill frame
- Width (due to spreading of slab)
  - Edge rollers (push material back)
  - Edge shears (cut material off)
- Length
  - End shears
- Mechanical Properties
  - Controlled by the microstructures which is controlled by the rolling parameters (reduction, temperature, etc)

Control of Overall Properties

- Tolerance
  - Thickness
    - Operator skill/automation
      - Gauges measure thickness of input and output
      - Computers control roll gap
  - Camber
    - Roll bending/automation
      - Special segmented tension meters measure "shape"
      - Computers bend the rolls
- Surface finish
  - Roll finish