Principles of Hot Rolling
The Art & Science

Comparison of Hot Rolling Processes

Antiquated Hot Strip Rolling Process
- Ingot Casting
- Skewing Mill
- Produced Slab (17-18 in.)
- HSM Hot Mill Furnace
- HSM Roughing
- HSM Finishing
- HSM Cooling

Hot Plate Rolling Process
- Continuous Casting
- Produced Slab (16-18 in.)
- HSM Hot Mill Furnace
- Plate Roughing
- In-Line Plate Processing

Conventional Hot Strip Rolling Process
- Continuous Casting
- Produced Slab (7 to 8 in.)
- HSM Hot Mill Furnace
- HSM Roughing
- HSM Finishing
- HSM Cooling

Thin Slab Hot Strip Rolling Process (Compact Steel Processing - CSP)
- Thin Slab Casting
- Produced Slab (2 to 3 in.)
- Tunnel Furnace
- HSM Finishing
- HSM Cooling

Thin Strip Rolling Process (CASTRIP®)
- Thin Strip Casting (0.005 - 0.175 in.)
- HSM Finishing
- HSM Cooling
Where does a Hot Strip Mill fit in the flat-roll production process?

1. Slab
2. Continuous reheating furnace
3. Roughing mill
4. Scale breaker
5. Finishing mill
6. Coiler
7. Continuous picking line
8. Teadem cold mill
9. Continuous annealing line
10. Electrolytic cleaning line
11. Batch annealing furnace
12. Tempering mill
13. Hot rolled coil
14. Cold rolled coil
**Why Roll at High Temperatures?**

• To lower the strength of a metal and improve its plasticity so that significant thickness reductions can occur.

• To achieve the proper starting point phase for control of transformation during the hot rolling process.

• To utilize the metallurgical mechanisms of recovery and recrystallization to soften the steel during deformation so that more reduction can be taken.

• To refine the as-hot rolled properties through mechanisms such as precipitation that do not occur at ambient (room) temperatures.

• To provide sufficient thickness reduction to eliminate the as-cast microstructure and produce a ‘wrought’ product that eliminates inherent casting defects.

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**Hot Rolling Basic Objectives**

- **Geometry / Size:** Produce a customer specific size and geometry starting from a slab.
  - Thickness, Width, Length, Weight, Flatness, Straightness, Crown, Edge Drop

- **Metallurgical Properties:**
  - State of precipitation of certain elements.
  - Grain refinement.
  - Preparation of product for subsequent treatment such as CR and annealing or to meet customer requirements for a HR product.

- **Internal Soundness:** Produce a ‘wrought’ product for improved compactness and internal soundness of the product.

- **Surface:** Produce a semi-uniform surface appearance free of defects.
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SHEET THICKNESS REDUCTION

- Pass work piece through the gap between two rolls rotating in opposite directions.
- The work piece is carried through by friction.
- Desired final thickness obtained by a series of such passes in succession.

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SHEET GEOMETRY CONTROL

- **Practical Problem:** Obtain final strip geometry through optimizing the reduction sequence (number of passes and reduction per pass) while at the same time:
  - Respecting certain metallurgical constraints
  - Respecting operating equipment constraints

- **Required Geometric Parameters:**
  - Thickness
  - Width
  - Flatness
  - Straightness (Camber)
  - Profile (Crown / Edge Drop)
Principles of Hot Rolling
GEOMETRY CONTROL – WIDTH REDUCTION

Starting Width

Ending Width

Width Reduction

Rolling Direction

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GEOMETRY CONTROL – FLATNESS

Edge Wave

Center Buckle

Making, Shaping and Treating of Steel: 101
Principles of Hot Rolling

GEOMETRY CONTROL – COIL SET & CROSSBOW

Coil Set

Crossbow

Making, Shaping and Treating of Steel: 101

11/2/2020
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GEOMETRY CONTROL – STRAIGHTNESS / CAMBER

Figure 1. Measurement of edge camber

Strip Crown = A + B

Edge Drop = F - H

Cross-Sectional Thickness Variation

Plot of Cross-Sectional Thickness Variation

Edge Drop = F - H

WIDTH

THICKNESS

Strip Crown = A + B
Principles of Hot Rolling

EQUIPMENT CAPABILITY – ROLLING CONSTRAINTS

- Rolling cannot occur outside of typical mill electrical and mechanical constraints:
  - Torque
  - Roll Force
  - Stand Speed
  - Stand Power
  - Stretch Limitations of Mill Housings

- Violation of Equipment Capability:
  - Thickness too light for a given width
  - Rolling temperature too cold
  - Deformation too extensive

Key Operating Variables

- The sequence of entry and exit thickness (reduction schedule).
- The radius of the rolls (which varies with time and loading force).
- The roll rotational speed.
- Front and back tension forces.
- The deformation behavior of the metal being rolled (rheology).
- Friction between the metal workpiece and the rolls (tribology).
- Temperature of the metal workpiece throughout the process.
- Time during rolling of each pass.
- Total time to roll to final hot band thickness.
Principles of Hot Rolling
METALLURGICAL CONSIDERATIONS
Thermo-Mechanical Processing

- Often referred to as ‘thermo-mechanical processing’ because metallurgical output is a function of temperature and mechanical deformation during rolling. Time is also a factor during hot rolling.

- Controlling grain size through the cross-section.

- Controlling size and distribution of precipitates in the hot band.

HSM Raw Material
Steel Slabs
HSM Raw Material

STEEL SLABS

- Sheet hot rolling mills begin with a continuously cast steel slab.

- Slab Dimensions
  - Thickness: 8” through to 10”
  - Width: 33” through to 60”
  - Length: 354” maximum (1000 PIW @ 10” thick)

- Slabs must be free of surface defects.

- Slabs must be properly scarfed (removal of casting defects).

- Slabs must be manufactured from liquid steel to the proper chemistry. Once solidified, the chemistry cannot change.

Mill Configuration

Equipment
HEATING: Slab is heated to temperature required for rolling (2400°F) via combustion of natural gas.

Goal is to heat slab evenly through the thickness:
- To prevent slab from being too cold during rolling downstream
- To ensure uniform austenite grain size through the slab thickness
- To guarantee precipitates are completely dissolved

Slab temperature is controlled by:
- Temperature set-points
- Pacing through the furnace (dropout rate)
SOAK = even heating through the cross-section of a slab

Slab Temperature:
2300 to 2400°F

NLMK Pennsylvania – Slab Drop Out
Mill Configuration

REHEAT FURNACES

Slab Extraction

Mill Configuration

REVERSING ROUGHING MILL

- **WIDTH REDUCTION:** Slab width is reduced up to two inches with the vertical edging rolls (squeeze).

- **THICKNESS REDUCTION:** Roughing mill reduces slab thickness in five (5) to seven (7) reversing passes down to 1.125” (transfer bar).

- **DESCALING:** High pressure descale water on entry side of mill removes remnant furnace scale and re-oxidation.
Mill Configuration

REVERSING ROUGHING MILL

MILL DESIGN: Four-High = 2 Back-Up Rolls + 2 Work Rolls

- Edger Roll (Width Control)
- Entry Descale
- Back-Up Roll (Undriven)
- Work Roll (Driven)

Back-Up Roll

Work Rolls

R3

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Mill Configuration
REVERSING ROUGHING MILL

Transfer Bar
Temperature: ~1940°F

Mill Configuration
VERTICAL EDGER ROLLS

Edger Roll Housing
Edger Roll (Width Reduction Max 2 in.)
Mill Configuration

VERTICAL EDGER ROLLS

Edger Roll (Width Reduction Max 2 in.)

Bottom Driven Edger Rolls

Mill Configuration

REVERSING ROUGHING MILL

A Transfer Bar headed to the Coil Box (1.125 in. thick)
Mill Configuration

COIL BOX

- **TEMPERATURE RETENTION**: Maintains a consistent temperature front to back during rolling through the Finishing Mill.

- **ROLLING POWER REDUCTION**: Power reduction of 13% on average equating to an energy savings of about 6% (Stelco statistics).

- **COBBLE REDUCTION**: Coils can be held for short delays and cooling is minimized.

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COIL BOX

1. Incoming hot transfer bar coiled CLOCKWISE in the coil box.

2. Coiled transfer bar uncoiled COUNTER CLOCKWISE into the finishing mill.
Mill Configuration

COIL BOX – THERMAL DROPOFF IMPROVEMENT

Coilbox (Temperature change about +10°C)
Too cold to roll long transfer bars

Conventional (Temperature change about -80°C)

Mill Configuration

COIL BOX

Peeler Arm
Mill Configuration

COIL BOX

FINISHING MILL

- **THICKNESS REDUCTION:** Final, continuous reduction to hot band gauge to a controlled variation tolerance (AGC).

- **STEEL PROPERTIES:** Temperature, reduction, and speed in part control the final properties of the hot band exiting the last stand.

- **GEOMETRY:** Profile and flatness are controlled through stand reduction, roll bending, and work roll grinding practices. Sheet width is not significantly changed.

- **SURFACE:** Rolled in scale is a bad thing. Controlling Finishing Mill parameters can determine whether or not it is present.

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**Mill Configuration**

FINISHING MILL

- **650 fpm**
- **890 fpm**
- **1380 fpm**

- Back-Up Roll (Undriven)
- Work Roll (Driven)
- Entry Side Guide
- Looper (Interstand Tension Control)

**FM Stand**

- Back-Up Roll
- Work Rolls
Mill Configuration
FINISHING MILL

FM Stand
Back-Up Roll
Work Rolls
Finishing Temperature = 1575 – 1680°F

Looper (controlling tension between F1 and F2)
Mill Configuration
FINISHING MILL – WORK ROLL CHANGE

Looper (controlling tension between F1 and F2)

Mill Configuration
RUNOUT TABLE / STRIP COOLING

- STRIP COOLING: Cools strip to appropriate temperature for coiling via application of water to top and bottom surfaces.
- TOP SURFACE COOLING: Laminar water curtains, slotted curtains.
- BOTTOM SURFACE COOLING: Spray bank curtains.
- STEEL PROPERTIES: The target temperature (coiling temperature), the rate of cooling (quench), and the cooling delay together with finishing mill variables, play a role in the steel properties acquired.
Mill Configuration

RUNOUT TABLE / STRIP COOLING

Strip After Cooling: Temperature 1000 – 1300°F

WINDING:
- Strip is over 4,000 ft. in length. The downcoilers wrap strip into a coiled hot band.

WINDING INTEGRITY:
- Laps should be wound onto themselves. Coiled hot band should be free of telescoping and sidewall oscillation. Oscillation leads to damage during handling.
Mill Configuration

DOWNCOILERS
Mill Configuration

HYDRAULIC PINCH ROLL
HYDRAULIC SIDEGUIDE
WRAPPER ROLL
COILER FRAME
MANDREL SUPPORT
MANDREL

The Final Product

HOT BANDS – THE FINISHED PRODUCT
**Winding Integrity**

OSCILLATED COILS

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**The Final Product**

SLAB TO HOT BAND

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BEFORE

AFTER
Basic Hot Rolling Defects
Mechanisms of Formation

Principles of Hot Rolling
ZERO DEFECTS

Making, Shaping and Treating of Steel: 101
**Principles of Hot Rolling**

**ROLLED-IN SCALE**

- **ROLL SURFACE BREAKDOWN:** Excessively worn work rolls microcrack under extremes of heat and pressure. The cracks coalesce to form small voices in the rolls. Scale packs in the voids and imprints onto the strip. The scale is further rolled in during later stand reductions.

- **IMPROPER DESCALING:** Rescale streaks rolled into the strip surface when a descale nozzle is plugged or damaged at the RRM or ahead of F1.

- **HIGH COILING TEMPERATURE:** A tertiary oxide forms during slow cooling after the steel is coiled up when the coiling temperature is set too high. This type of scale is difficult to remove via acid pickling.
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ROLLED-IN SCALE

Worn Roll Pattern Scale

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LAMINATIONS / SLIVERS

• MELT / CAST SOURCES: Hard inclusions at the surface respond different to plastic deformation during rolling. Surface tears can occur at high temperature in the mold during continuous casting – fluxing issues (slivers).

• MECHANICAL SURFACE TEARS - REHEATING: Slab bottom surface tears occurring due to abrasive contact with the load bearing, water cooled skid rails at high temperature in the slab reheat furnaces. Defect is transverse so rolls out to a diagonal with respect to the rolling direction (skid tear).

• MECHANICAL SURFACE TEARS - ROLLING: Any source intruding into the pass line of the slab / strip as it rolls can create surface gouges. Rescale packs into the gouge, rolls into the surface as metal flows over top of the scale during subsequent rolling passes. With significant reduction, the non-metallic scale can burst back through the surface at the HSM or during cold rolling.
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LAMINATIONS / SLIVERS

Reheat Furnace Skid Tear Lamination

Lamination / Hole ("Birds-In-Flight")

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MECHANICAL LAMINATIONS / SKID TEAR

Severe Peeling Mechanical Lamination (subsurface non-metallic visible)
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ROLL MARKS / BRUISES

- **ROLLING SOURCES:** Any mark on a work roll imprints a repeating pattern on the strip surface at a frequency of $2\pi R$, where $R$ is the radius of the source work roll.

- **COILING SOURCES:** The downcoiler pinch rolls and blocker rolls are not performing gauge reduction on the strip, but they are typically operated under enough pressure that marks on the rolls will imprint onto the strip surface. Blocker roll marks will tend to be present on only the coil ends since this is the only portion of the strip where they are used.
Principles of Hot Rolling
SCRATCH DEFECTS

• HIGH TEMPERATURE SCRATCHES: Any source of surface scribing intruding into the rolling pass line creates a scratch. Scratches occurring in vicinity of the rolling mills will have a ‘rolled over’ appearance with little to no surface relief. They will also appear heavily oxidized.

• LOW TEMPERATURE SCRATCHES: Scratches sourced from locations after the rolling mills may have surface relief to them. If the strip temperature are still high enough, they will appear oxidized. As a rule of thumb, scratches that are bright or metallic shiny in appearance are sourced after the Hot Strip Mill.
Physical Metallurgy of Thermo-Mechanical Processing
Less Art, More Science

Principles of Hot Rolling
PHYSICAL METALLURGY

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Principles of Hot Rolling

PHYSICAL METALLURGY - REHEATING

- Reheating temperature must be high enough to dissolve fine particles in the steel slab (precipitates).

- Undissolved precipitates cannot be re-precipitated during rolling and will NOT participate in mechanisms of strengthening.

- Microalloying additions in HSLA such as Nb (niobium) or V (vanadium) initially suppress grain coarsening followed by rapid, abnormal grain growth when particles dissolve at higher reheating temperatures.

- Microalloying additions in 1001 (IF) such as Ti (titanium) inhibit grain coarsening during the entire reheating cycle.

- Practically, too high a reheating temperature can lead to ‘burning’ (melting at the grain boundaries) or ‘scale washing’ (melting and fusing of FeO oxide scale to slab surface).
High Temperature Deformation of Austenite

FCC Phase of Steel

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HIGH TEMPERATURE DEFORMATION of AUSTENITE

• **COARSE GRAINED EQUIAXED AUSTENITE:** This is the starting point microstructure of the rolling deformation process.

• **DYNAMIC RECRYSTALLIZATION:** Occurs during steel deformation in the mill roll bite. Involves reduction in work hardening (small effect).

• **STATIC RECRYSTALLIZATION:** Occurs after the reduction pass is complete. Occurs spontaneously as new grains grow on pre-existing grain boundaries.
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HIGH TEMPERATURE DEFORMATION of AUSTENITE

Example of what happens at the Roughing Mill

INITIAL GRAIN SIZE: Because new grains nucleate and grow at grain boundaries, time for recrystallization and final grain size are a function of initial grain size.

EFFECT OF REDUCTION & TEMPERATURE: For a given reduction, the extent of austenite recrystallization is a function of the slab temperature.
Principles of Hot Rolling

HIGH TEMPERATURE DEFORMATION of AUSTENITE

- **INITIAL GRAIN SIZE:** Because new grains nucleate and grow at grain boundaries, time for recrystallization and final grain size are a function of initial grain size.

- **EFFECT OF REDUCTION & TEMPERATURE:** For a given reduction, the extent of austenite recrystallization is a function of the slab temperature.

- **EFFECT OF MICROALLOYING:** Elements such as Nb (Niobium) in HSLA slow down dynamic and static recrystallization processes producing more of a deformed austenite microstructure.
Principles of Hot Rolling
EFFECT OF MICROALLOYING ELEMENTS

CASE STUDY II
HSLA Grade
(Effect of Nb in Microalloyed Steel)

Small amount of Nb leads to higher temperature required for full restoration.

CASE STUDY I
1006 Grade
(Effect of Al in C-Mn Steel)

% ELEMENT CONCENTRATION

Low Temperature Refinement of Ferrite
BCC Phase of Steel

Making, Shaping and Treating of Steel: 101
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LOW TEMPERATURE REFINEMENT of FERRITE GRAIN SIZE

- Austenite finally transforms to ferrite late in the Finishing Mill or on the Runout Table.

- Ferrite grain size is affected by:
  - Finishing Temperature (measured at exit of last stand)
  - Delay Time between last stand and first water curtain
  - Cooling Rate and Cooling Target (CCT Diagram applies)

- Ferrite grain size is smaller as:
  - Finishing Temperature is decreased
  - Cooling Rate is increased
  - Coiling temperature set-point is decreased

- Smaller ferrite grain size leads to enhanced properties.

PRECIPITATION STRENGTHENING

- Why is microalloyed HSLA harder to hot roll than 1006?
  - Nb (niobium) combines with C (carbon) to form niobium carbide particles (precipitates) in austenite.
  - The particles strengthen the material by inhibiting austenite recrystallization (deformed austenite).
  - The Solute Drag Effect: Nb atoms are larger than Fe atoms which inhibits recrystallization (deformed austenite).
  - Material produced is of higher strength (55 vs. 35 ksi yield strength) which leads to higher loads in the mill.

- Why is a V-bearing HSLA steel easier to roll?
  - V-carbides and nitrides form in ferrite, not austenite.
  - Strength from precipitation is achieved during cooling outside of the finishing mill on the run-out table.
Principles of Hot Rolling

PRACTICAL DIFFERENCES IN ROLLING PERFORMANCE

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<th>Size</th>
<th>Grade</th>
<th>1001</th>
<th>1006</th>
<th>HSLA</th>
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<tr>
<td>Grade</td>
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<tr>
<td>Incoming Tmp (°F)</td>
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<td>1,820</td>
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<tr>
<td>CT (°F)</td>
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<tr>
<td>YS (psi)</td>
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<td>36,300</td>
<td>63,400</td>
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<tr>
<td>TS (psi)</td>
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<td>52,400</td>
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<td>Elongation (%)</td>
<td>39%</td>
<td>35%</td>
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Principles of Pickling Processes

Hot Rolled Scale Removal
Hot Mill Scale Layers

Hot Rolled ‘Black’ Bands

Hot Rolled Pickled Bands (HRPO)
Pickle Line - Entry End

Cracks are induced in the scale to promote HCl acid penetration.
**Induced Cracks**

![Diagram of induced cracks](image)

**Pickle Line – Chemistry**

\[
\text{Fe}_2\text{O}_3 + 6\text{HCl} \rightarrow 2\text{FeCl}_3 + 3\text{H}_2\text{O}
\]

\[
\text{Fe}_3\text{O}_4 + 8\text{HCl} \rightarrow \text{FeCl}_2 + 2\text{FeCl}_3 + 4\text{H}_2\text{O}
\]

\[
\text{FeO} + 2\text{HCl} \rightarrow \text{FeCl}_2 + \text{H}_2\text{O}
\]

<table>
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<th>Tank 4</th>
<th>Tank 3</th>
<th>Tank 2</th>
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<tr>
<td>7% HCl</td>
<td>5% HCl</td>
<td>3% HCl</td>
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<tr>
<td>7% FeCl₂</td>
<td>9% FeCl₂</td>
<td>11% FeCl₂</td>
<td>13% FeCl₂</td>
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strip direction
Pickle Line - Accumulator

Approx. 300 ft. of strip storage

Pickle Line – Edge Trimming
Pickle Line – Edge Trimming

As-Hot Rolled Mill Edge

Model of a Pickled, Trimmed (Cut) Edge
Pickle Line – Delivery End