TECHNOLOGICAL DEVELOPMENTS IN COLD ROLLING MILLS

- Development of Cold Rolling Mills
- Automation Systems

S Avhad
Flat Products Equipment Ltd
THE INDIAN SCENE

- Hot Rolling at TISCO – 1930s
- Cold Rolling only in late 1950/1960s with integrated steel plant.
- Rapid growth from 1978 to 1990.
TECHNOLOGY LEVELS OF COLD ROLLING MILLS

- 1970 to 1977 - Narrow 2 Hi / 4 Hi
- 1977 to 1982 - Hydraulically Operated Cold Rolling Mill
- 1982 to 2000 - Wider (1300 mm) faster & 6-Hi
- 2000 onwards - Wider (1650 mm), faster & technologically state-of-art, fully automated.
SOME TYPICAL TYPE OF MILLS

- SENDZIMIR MILL
  - As-U-Roll Eccentric Arrangement
  - Crown Control and Mill Shape
  - Z-High Mill
- 6-Hi Mill
  - H-C Mill
  - U-C Mill
- 4-Hi / 6-Hi ‘CVC’ Mill
AS-U-ROLL ECCENTRIC ARRANGEMENT – SENDZIMIR MILL
Crown Control and Mill Shape – SENDZIMIR MILL

1. Pay Off Reel
2. Pinch Roll Cum Flattner
3. Entry Tension Reel
4. Deflector Roll
5. Unwinder
6. Belt Wrapper
Z-High Mill - basic configuration

Flat Products Equipments

Top Back-up Roll
Intermediate Roll
Work Rolls
Intermediate Roll
Bottom Back-up Roll
Z-High Mill - basic configuration

1. Drive Side
2. Operator Side
3. Top And Bottom Back Up Roll
4. Top And Bottom IMR Roll
5. Top And Bottom Work Roll
6. Pass Line
H-C Mill

HC MILL CONFIGURATION

1) Work Rolls
2) Intermediate Roll
3) Back-up Rolls
U-C Mill

UC MILL CONFIGURATION

1) Work Rolls
2) Intermediate Roll
3) Back-up Rolls
4-Hi / 6-Hi ‘CVC’ Mill
4-Hi / 6-Hi ‘CVC’ Mill

CVC MILL CONFIGURATION

1) Work Rolls
2) Back-up Rolls

[NEGATIVE CROWN]  [NEUTRAL CROWN]  [POSITIVE CROWN]

PRINCIPLE OF CONTINUOUS VARIABLE CROWN SYSTEM
INDIGENOUS DESIGN & MANUFACTURING

- Started in 1969 – 70 with MECON with United Engineering, USA collaboration.
- Tata Davy followed with Davy Mckee collaboration.
- Many mill equipment builders on the scene.
- Precision Equipment / Flat Products formed in 1977 collaboration with T. Sendzimir.
  - 1st Hydraulic Screw Down Mill
  - 1st Sendzimir Mill for Carbon Steel
  - 1st 6-Hi Cold Mill (1000 mm)
  - 6-Hi - Widest (1650 mm) Cold Mill
  - 6-Hi - Fastest (1400 mpm) Cold Mill
  - 6-Hi Mill with AC Drives to China.
  - State-of-Art Automation
Automation Hierarchy

CONTROL SYSTEMS
Level 3: Production Level Automation
Level 2: Process Automation
Level 1: Basic Automation
Level 0: Actuation Level

PRODUCTS
ERP / MIS
Process Computer
PLC / DCS
Sensors, Motors, Drives
Control Desk, Valves

CONTROLLER
The Plant Manager
The Metallurgist
The Supervisor
The Worker

Flat Products Equipments
### Automation Control Functions Hierarchy in a Rolling Mill

<table>
<thead>
<tr>
<th>Level</th>
<th>Actuators &amp; Sensors</th>
<th>Controller</th>
</tr>
</thead>
</table>
| Level 0 | a) Line & Auxiliary Motors  
b) Drives  
c) Sensors (Proximity, Photo, Analog)  
d) Valves (Hydraulic, Pneumatic, Control) |            |
## Automation Control Functions

### Hierarchy in a Rolling Mill

<table>
<thead>
<tr>
<th>Level</th>
<th>Equipment Level Automation</th>
<th>Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1</td>
<td>a) Master Controls</td>
<td>The Engineer</td>
</tr>
<tr>
<td></td>
<td>b) Sequence Controls</td>
<td></td>
</tr>
<tr>
<td></td>
<td>c) Close Loop Controls</td>
<td></td>
</tr>
<tr>
<td></td>
<td>d) Uploading the Actual Rolling Data to Level 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>e) Generation of Reference based on Data provided by Level 2</td>
<td></td>
</tr>
</tbody>
</table>
### Automation Control Functions

#### Hierarchy in a Rolling Mill

<table>
<thead>
<tr>
<th>Level</th>
<th>Process Automation Level</th>
<th>Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 2</td>
<td>a) Mill Set-up Models</td>
<td>The Engineer</td>
</tr>
<tr>
<td></td>
<td>b) Maintenance of the Data Base of down loaded PDI</td>
<td></td>
</tr>
<tr>
<td></td>
<td>c) Selection of PDI for particular Coil</td>
<td></td>
</tr>
<tr>
<td></td>
<td>d) Selection of suitable Pass Schedule</td>
<td></td>
</tr>
<tr>
<td></td>
<td>e) Collection of Rolled Coil Data</td>
<td></td>
</tr>
</tbody>
</table>
### Automation Control Functions Hierarchy in a Rolling Mill

#### PRODUCTION AUTOMATION LEVEL – PC BASED SYSTEM

<table>
<thead>
<tr>
<th>Level</th>
<th>Automation Hierarchy</th>
<th>Controller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 3</td>
<td><strong>a) ERP Packages</strong>&lt;br&gt;b) MIS Systems&lt;br&gt;c) Plant-wise Production Planning</td>
<td>The Plant Manager</td>
</tr>
</tbody>
</table>
Main tasks of a model system

- Scheduling for yield and quality
- Thread setup for gauge/shape
- Operating mode selection
- Mill speed and drive selection
- Control gain calculation
- Mill observation
- Reporting / Logging

Application in:
4high, 6high, 20high
HMI examples
HMI with soft-sensing
Force and power models

Main Models

Plastic deformation (numerical method):

$$\frac{d\sigma_{z}(\ddot{u})}{d\bar{\sigma}} = 2 \cdot \tilde{R}_{WR} \cdot \cos(\ddot{u}) \cdot \left[ \sigma_{t}(\ddot{u}) \cdot \tan(\ddot{u} - \ddot{\alpha}) - \sigma_{z}(\ddot{u}) \cdot \left( \tan(\ddot{u}) - \tan(\ddot{\alpha}) \right) \right]$$

Elastic parts (analytical method):

$$F_{R,el} = w \cdot \frac{2}{3} \cdot \left( \frac{2}{\sqrt{3}} \cdot k_{f1} - \sigma_{1} \right) \cdot \sqrt{E_{WR} \cdot h \cdot \tilde{R}_{WR} \cdot \left( 1 - \nu_{roll}^{2} \right) \cdot \frac{2}{\sqrt{3}} \cdot k_{f1} - \sigma_{1}}$$

Yield stress (flexible adaptive method):

$$k_{f} = t_{adapt}(\rho, \phi, n, k_{adapt}) \cdot t_{init}(\rho, \phi, n, k_{init})$$

Fricion (transition from dry to hydrodynamic friction):

$$\mu(\alpha) = \mu_{dry} + (\mu_{hydro} - \mu_{dry}) \cdot \frac{v_{0} + v_{WR} \cdot \frac{3 \cdot \eta_{lip,obar} \cdot a_{p,ub} \cdot (v_{0} + v_{WR})}{\alpha_{0} + 1 - e^{-a_{p,ub} \cdot (v_{0} + v_{WR}) \cdot \frac{\eta_{lip,obar}}{h_{WR} + r_{S}}}}}{v(\alpha) + v_{WR}}$$

Further components:
- Flatening
- Temperature
Force and power models

Comparison at a Sendzimir mill for stainless steel

Comparison at a 6-high non-ferrous mill
Temperature Models

Main models

Coil cool down (empirical):
\[ \Delta \theta_{\text{form}} = \left( \frac{F_R}{Id \cdot w} \right) \cdot \frac{2}{\sqrt{3}} \cdot \ln \left( \frac{h_0}{h_1} \right) \cdot \frac{1}{\kappa_s \cdot \rho_s} \]

Forming energy:

Heat exchange with rolls:
\[ \Delta \theta_{\text{cond}} = \frac{2 \cdot k_{th} \cdot Id}{\rho_s \cdot \kappa_s \cdot h_1 \cdot v_1} \cdot (\theta_{WR} - \theta) \]

Strip and roll coolant:
\[ \Delta \theta_{\text{cool}} = \frac{\rho_c \cdot \kappa_c \cdot Q_c}{\rho_c \cdot \kappa_c \cdot Q_c + \rho_s \cdot \kappa_s \cdot Q_s} \cdot (\theta_{\text{start}} - \theta_{\text{cool}}) \cdot e^{-\frac{w_Nu_{\text{cond}} \cdot \kappa_s}{\theta_{\text{end}} - \theta_{\text{end}} - 1}} \]
Roll temperature model
Geometry and shape models

Main models (here for a 6-high mill)

Elastic deformation via finite beam elements

\[ \beta_{cr}^* = \frac{\partial \cdot M_{B,r}(x)}{E_r \cdot \pi \cdot D(x)^4} \quad \text{in case that} \quad \|\beta_{cr}^*(x)\|^2 \ll 1 \]

Flattening between rolls

\[ u(x) = 2 \cdot (1 - \nu_r^2) \cdot \frac{f(x)}{\pi \cdot E \cdot l(x)} \left[ \ln \left( \frac{D(x)}{l(x)} \right) + K \right] \]

Flattening of strip into work rolls

\[ u = \frac{2 \cdot (1 - \nu_r^2)}{\pi \cdot E \cdot w} \cdot \ln \left( \frac{D}{l} \right) + \frac{0.55 \cdot F}{E \cdot w} \left( 1 + \frac{2 \cdot |x - w|}{D} \right)^{10/3} \]

Shape model - interaction of strip and work rolls

Further components:
- Thermal roll crown
- Roll wear
- Adaptation
Shape optimization and adaptation:

Least mean square to minimise difference.

\[
\frac{\partial}{\partial \Delta \psi_l} \int_{-0.5w}^{+0.5w} \left( \Delta \sigma_1(x, \psi_k) + \sum_{k=1}^{K} \frac{\partial \Delta \sigma_1(x, \psi_k)}{\partial \psi_k} \cdot \Delta \psi_k - \Delta \sigma_{1, \text{target}}(x) \right)^2 \cdot dx = 0 \quad l = 1, \ldots, K
\]
Further components

Automatic adaptation of yield stress

**Example**: Yield stress of 304 stainless steel

- **Yield stress from adaptation**
- **Yield stress from torsion bar test**
Technological functions

Interaction of models and technological functions

- Targets
  - Pass schedule optimisation
  - Force and torque
  - Temperature effects
  - Drive power
  - Friction
  - Yield stress

- Correction of relevant parameter Adaptation

- Setup Gauge
  - Geometry/Flattening
  - Flatness/Profile

- Setup Flatness
  - Dynamics of rolls and adaptation preview

- Process
  - References
  - MILL
  - Pre-sets
Results

Production results reached at a prototype for 20-high mills

<table>
<thead>
<tr>
<th>Used mode</th>
<th>Number of coils rolled</th>
<th>Number of coils with quality problems</th>
<th>Productivity related to rolling time</th>
<th>Productivity related to total time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual</td>
<td>1083</td>
<td>21 (≈2.0%)</td>
<td>100.0 %</td>
<td>100.0 %</td>
</tr>
<tr>
<td>Modell</td>
<td>4250</td>
<td>15 (≈-0.4%)</td>
<td>104.5 %</td>
<td>105.0 %</td>
</tr>
</tbody>
</table>

Summary:
Depending on the evaluation basis, the productivity increase varies between 4.5% and 6.6%