ADVANCES IN SPECIAL STEEL PRODUCTS INCLUDING STAINLESS STEELS

DR. L. K. SINGHAL
AMRITRAJ BHANJA
JSL STAINLESS LTD
CONSERVATION OF DEPLETING ENERGY & RAW MATERIAL RESOURCES

LOWER LIFE CYCLE COST

MAJOR DRIVING FORCES

INCREASING PROPERTY REQUIREMENTS

GREATER FOCUS ON AESTHETIC APPEAL
ADVANCED HIGH STRENGTH STEELS

HIGH STRENGTH
- WEIGHT REDUCTION
- LOWER COST

ENHANCED FORMABILITY
- GREATER COMPONENT FLEXIBILITY
- FEWER COMPONENTS
MICRO-ALLOYED STEEL (HSLA)

- Micro-alloying of V, Nb, Ti
- Strengthening
  - Solid Solution (P, Mn, Si)
  - Precipitation & Grain Refinement (Nb, V)
- Medium & High Strength, Moderate Formability
  - YS: 250-700 MPa
  - T-El: 20-35 %.
DEVELOPMENT OF HIGH STRENGTH MICRO-ALLOYED PIPELINE STEELS
## MICRO-ALLOYED STEEL APPLICATIONS

<table>
<thead>
<tr>
<th>LINEPIPES (GAS/OIL)</th>
<th>BUILDING STRUCTURES</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEAVY DUTY VEHICLES</td>
<td>MINING &amp; AGRI INDUSTRY</td>
</tr>
<tr>
<td>TRANSMISSION TOWERS</td>
<td>SHIP BUILDING</td>
</tr>
</tbody>
</table>

**HIGH RISE BUILDING STRUCTURES**

**PIPCLES**
### MATERIAL SAVING

<table>
<thead>
<tr>
<th>Material Grade</th>
<th>Wall thickness (mm)</th>
<th>Overall Project Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>X70</td>
<td>20.8</td>
<td></td>
</tr>
<tr>
<td>X80</td>
<td>18.3</td>
<td></td>
</tr>
<tr>
<td>X100</td>
<td>15.9</td>
<td></td>
</tr>
<tr>
<td>X120</td>
<td>12.7</td>
<td></td>
</tr>
</tbody>
</table>

**Graph:**

- **Y-axis:** Pipeline weight (t)
- **X-axis:** API Steel grade
- **Bars:**
  - **X70:** 165000 t
  - **X80:** 145000 t
  - **X100:** 126000 t
  - **X120:** 101000 t
DUAL PHASE STEEL

- Alloying with Mn, Si, Cr, Mo etc.
- Coiling at Low Temperature
- Islands of Martensite in Ferrite.
- Grain Refinement and Precipitation Strengthening (Nb, Ti, V etc.)
- Solid solution strengthening (Mn, P, Si etc.)
METALLURGICAL ASPECT TO OBTAIN DP STEEL

I - heating

II - soaking

- Formation of Austenite

III - slow cooling

- Formation of Ferrite

IV - quenching

V - Tempering

Initial microstructure: F+B+P+(M)

I + II - Formation of Austenite

III - Formation of Ferrite

IV - Formation of Martensite/Bainite

V - Tempering of Martensite/Bainite
DP STEELS ARE BAKE-HARDENABLE.

INCREASE IN YIELD STRENGTH IN DP STEELS OF ABOUT 140 MPa AFTER FORMING & BAKING.

LIMITED INCREASE IN YS BY WORK HARDENING IN HSLA DUE TO HIGH YS/TS RATIO.
# Dual Phase Steel Applications

<table>
<thead>
<tr>
<th>Steel type</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>Nb (Cb)</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual Phase</td>
<td>0.08</td>
<td>0.30</td>
<td>0.50</td>
<td>0.07</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>0.07</td>
<td>0.49</td>
<td>1.59</td>
<td>-</td>
<td>0.038</td>
<td>1.59</td>
</tr>
</tbody>
</table>

## Reinforcements

- **Automobile Wheel**
- **B-Pillar Reinforcement**
**MARTENSITIC STEEL**

**APPLICATIONS**

- Y.S. – ~1450 MPa
- T.S. – ~1650 MPa
- % Elongation (min) – 8

**ARMOUR STEEL**

<table>
<thead>
<tr>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Mo</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>1.0</td>
<td>0.6</td>
<td>1</td>
<td>0.3</td>
<td>50 ppm</td>
</tr>
</tbody>
</table>

**TANKS**
TRENDS IN MARTENSITIC STEEL

INITIALLY HIGH CARBON CONTENT (QUENCHED & TEMPERED)

ALLOYING WITH Ni, Mo FOR STRENGTH & TOUGHNESS (QUENCHED & TEMPERED)

PART SUBSTITUTION BY Mn, Cr, B (QUENCHED & TEMPERED)

MICRO-ALLOYING (V, Nb, Ti) – THERMO-MECHANICALLY CONTROLLED PROCESSING

Based on TMCP & Tempered Martensite

<table>
<thead>
<tr>
<th>C</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>V</th>
<th>Ti</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>HY</td>
<td>0.15</td>
<td>3</td>
<td>1.5</td>
<td>0.5</td>
<td>0.03</td>
<td>0.02</td>
<td>&lt;0.015</td>
</tr>
</tbody>
</table>

- Y.S. – 551 MPa (min.)
- % Elongation (min) – 20
- Charpy Impact – 47.5 Joules @ -49 °C
TRIP STEEL

- Suppress Pearlite by rapid cooling.
- During inter-critical anneal, Carbon in Austenite increases.
- Suppress Cementite by Silicon addition.
- Austenite retained - Transforms during deformation
- TRIP 590/690/780
METALLURGICAL ASPECT TO OBTAIN TRIP STEEL

<table>
<thead>
<tr>
<th>Steel type</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIP Steel</td>
<td>0.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>0.14</td>
<td>1.95</td>
<td>1.65</td>
</tr>
</tbody>
</table>

AUTOMOBILE STRUCTURAL & SAFETY PARTS:
- Cross members.
- Longitudinal beams.
- B-pillar reinforcements.
- Sills and bumper reinforcements.
# High Strength Austenitic Stainless Steels - Metastable

<table>
<thead>
<tr>
<th>Grade</th>
<th>C</th>
<th>Cr</th>
<th>Mn</th>
<th>Cu</th>
<th>S</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>JSLT</td>
<td>≤ 0.1</td>
<td>15.0-16.0</td>
<td>9.0-10.0</td>
<td>1.5-2.0</td>
<td>≤0.01</td>
<td>0.1-0.2</td>
</tr>
</tbody>
</table>

![Graph showing tensile strength and elongation for different grades of stainless steel.](image-url)
Thickness of Bumper Reduced @ASHOK LEYLAND

3mm EDD BUMPER

1.2mm JSLT BUMPER

Theoretical FLD

Major strain

Minor Strain
TWIP STEEL X5 MN AL SI 25 3 3

Deformed sample (uniform elongation of 70%)

Sample after twisting by 1080° (T = 20 °C)
High Nitrogen Austenitic Stainless Steel
DIN 1.3816 -X8CrMnN18-18

<table>
<thead>
<tr>
<th>C</th>
<th>Cr</th>
<th>Mn</th>
<th>N</th>
<th>Si</th>
<th>P</th>
<th>S</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>17.5</td>
<td>17.5</td>
<td>0.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.1</td>
<td>20</td>
<td>20</td>
<td>0.7</td>
<td>0.8</td>
<td>0.06</td>
<td>0.015</td>
<td>Bal</td>
</tr>
</tbody>
</table>

Elongation (%) vs. Tensile Strength (MPa)

- IF
- IF-HS
- MILD
- BH
- CMn
- TRIP Low Alloy
- Dual Phase
- HSLA
- TWIP
- X-IP (24Mn-0.5C-Al)
- HIGH NITROGEN AUSTENITIC
  18Cr-18Mn-0.5N
- TRIP AUSTENITIC S.S.
- MART
# Interstitial Free Ferritic Stainless Steels

**Advantage**
- Improved Corrosion resistance
- Superior Formability
- Improved Weldability
- Superior Toughness
- Lower DBT Temp.

<table>
<thead>
<tr>
<th>Grade</th>
<th>%C</th>
<th>%Cr</th>
<th>%Ti/(Ti + Nb)</th>
<th>%Mo</th>
<th>%N</th>
</tr>
</thead>
<tbody>
<tr>
<td>409L</td>
<td>0.01</td>
<td>11</td>
<td>~ 0.2</td>
<td>-</td>
<td>0.01</td>
</tr>
<tr>
<td>436L</td>
<td>0.01</td>
<td>16</td>
<td>~ 0.3</td>
<td>1</td>
<td>0.01</td>
</tr>
<tr>
<td>439</td>
<td>0.01</td>
<td>17</td>
<td>~ 0.3</td>
<td>-</td>
<td>0.01</td>
</tr>
<tr>
<td>441</td>
<td>0.01</td>
<td>18</td>
<td>~ 0.5</td>
<td>-</td>
<td>0.01</td>
</tr>
<tr>
<td>444</td>
<td>0.01</td>
<td>18</td>
<td>~ 0.4</td>
<td>~2</td>
<td>0.01</td>
</tr>
<tr>
<td>446</td>
<td>0.1</td>
<td>23</td>
<td></td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Ti, Nb or Ti+Nb stabilized grades
Low C, Low N Ferritic Stabilized with Ti/Nb

Finding increasing application due to

- Comparable Corrosion Resistance  441 vs. 304 grade
- Superior Drawability : High r-bar value
- Good Ridging Resistance
- Superior Weldability in comparison to classical Ferritics

\[
\begin{align*}
441 & : 0.01C - 18Cr - 0.4(Ti+Nb) - 0.01N \\
304 & : 0.05C - 18Cr - 8Ni - 0.04N
\end{align*}
\]
Applications of 439

- Automotive exhaust manifolds and mufflers
- Direct fired hot water tanks
- Food equipments
- Lift panels
- Electrical appliances: Washing machine drum, microwave ovens
- Sugar industry: Sugar-cane juice ducts, heaters, evaporators, crystallization units

Applications of 441

- Solar panel
- Solar hot water tank, Solar Collector
- Exchanger tubes: Sugar & energy industry
- Exhaust system: manifold, catalytic converter
Applications of 409L

- Automobile exhaust system: Mufflers, manifold, Catalytic Converters
- Fuel filters
- Refrigerated container
- LCD monitor frames

Applications of 436L

- Solar water heater
- Visible parts of exhaust systems
- Automotive trim and outdoor panels
- Communication-system shelter
SUPER FERRITIC STAINLESS STEELS WITH HIGH CORROSION RESISTANCE

<table>
<thead>
<tr>
<th>Grade</th>
<th>Cr</th>
<th>Mo</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super Ferritic Corrosion Resistant</td>
<td>44626</td>
<td>25-27</td>
<td>0.75-1.5</td>
</tr>
<tr>
<td>Super Ferritic Heat Resistant</td>
<td>44600</td>
<td>23-27</td>
<td>-</td>
</tr>
</tbody>
</table>

**Applications**

- Boiler tubes
- Cement kilns
- Waste heat boilers
- Salt baths
- Heat treating
- Incinerators
STAINLESS STEELS WITH HIGH CORROSION RESISTANCE

- Improved Pitting Corrosion Resistance
- Improved Weldability
- Improved Formability–TRIP Optimization
- Reduced Material Cost
- Reduced Processing Cost

Benefits of Interstitial Nitrogen

Diagram showing various stainless steels with their PREN values and applications:

- **Biodur 108**
- **200 Series**: X8CrMn N18-18
- **400 Series**: 446
- **300 Series**: 904L, 316LN, 317L, 316N, 304, 301

Applications:

- **Sea Water 20 °C**
- **Sea Water Env.**
- **Industrial Env & Exteriors**
- **Water & Interiors**
- **Dry applications, Automotive Exhaust System, Railway Wagons, Cutlery, Razor Blade**
High Performance Austenitic Stainless Steels

<table>
<thead>
<tr>
<th>Grade</th>
<th>C</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>Cu</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>31727/NAS 155N</td>
<td>0.02</td>
<td>18</td>
<td>15</td>
<td>4</td>
<td>3</td>
<td>0.2</td>
</tr>
<tr>
<td>Super Austenitic EN 1.4529/NAS 255NM</td>
<td>0.01</td>
<td>20</td>
<td>25</td>
<td>6</td>
<td>1</td>
<td>0.2</td>
</tr>
</tbody>
</table>

APPLICATIONS

<table>
<thead>
<tr>
<th>31727</th>
<th>Chimneys and dampers of high sulfur fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dilute sulfuric acid tanks</td>
</tr>
<tr>
<td>EN 1.4529</td>
<td>Pollution control: Flue gas desulphurisation (absorber, ducts)</td>
</tr>
<tr>
<td></td>
<td>Natural and treated seawater system, desalination plants</td>
</tr>
<tr>
<td></td>
<td>Bleaching equipment for pulp and paper industries</td>
</tr>
<tr>
<td></td>
<td>Chemical industries: Phosphoric acid &amp; Sulphuric acid plants</td>
</tr>
</tbody>
</table>

CHIMNEYS

BLEACHING EQUIPMENT
# Duplex & Super Duplex Stainless Steels

Low carbon and intentionally added nitrogen for:
- Superior Inter-grannular corrosion resistance
- Higher pitting resistance
- Improved Weldability

<table>
<thead>
<tr>
<th>Grade</th>
<th>C</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>N</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lean Duplex</td>
<td>0.03</td>
<td>21</td>
<td>1.5</td>
<td>-</td>
<td>0.22</td>
<td>-</td>
</tr>
<tr>
<td>Duplex</td>
<td>0.02</td>
<td>22</td>
<td>5</td>
<td>3</td>
<td>0.16</td>
<td>-</td>
</tr>
<tr>
<td>Super Duplex</td>
<td>0.02</td>
<td>25</td>
<td>7</td>
<td>3</td>
<td>0.25</td>
<td>0.5</td>
</tr>
<tr>
<td>(UNS 32760)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(ZERON 100)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Nitrogen Alloying has made Duplex Stainless Steel Readily Weldable*
### APPLICATIONS

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Applications</th>
</tr>
</thead>
</table>
| **Lean Duplex 2101** | **Tanks:** Palm oil, Wine, Marble slurry, Potable and Sewage water, Ethanol, Fruit juice, Biodiesel  
**Infrastructure:** Bridges, Sluice gates |
| **Duplex 2205** | **Chemical industry:** Sour gas piping, Heat exchanger, tanks and vessels for chloride-containing media  
**Oil and Gas industry:** Piping and process equipment, offshore structures  
**Cargo tanks** in ships for transport of chemicals  
**Flue gas desulphurization** systems, Electrostatic precipitators  
**Pulp and Paper industry:** Digester |
| **Super Duplex 32760** | **Sea water Desalination Plants**  
**Sea water Pumps** |

### ROTARY PUMPS

![FLUE-GAS DESULFURISATION UNITS](image)
IT IS AMAZING THAT STILL GRADE 304 (18Cr-8Ni) ACCOUNTS FOR 50% OF TOTAL S.S PRODUCTION WORLDWIDE

N added Stainless Steels

0.05N nearly replaces 1%Ni

<table>
<thead>
<tr>
<th>Cost per Kg of Input Materials</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel Scrap</td>
<td>Rs 20</td>
</tr>
<tr>
<td>Cr (From HC Fe-Cr)</td>
<td>Rs 110</td>
</tr>
<tr>
<td>Mn (From HC Fe-Ni)</td>
<td>Rs 80</td>
</tr>
<tr>
<td>Nickel</td>
<td>Rs 1250</td>
</tr>
</tbody>
</table>
**Low Cost Alternatives to 18Cr-8Ni**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Applications</th>
<th>Switch To</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unwelded Application</td>
<td>Kitchenware, White Goods, Decorative Wares, Wall Panels</td>
<td>Cr 16+</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Grade</th>
<th>%C</th>
<th>%Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>430</td>
<td>0.1</td>
<td>16</td>
</tr>
</tbody>
</table>

| Welded Application with Corrosion Resistance Similar to 304 | Welded Tubes, Tanks, Exteriors | 439, 441, 444 |

<table>
<thead>
<tr>
<th>Grade</th>
<th>%C</th>
<th>%Cr</th>
<th>%Ti/(Ti + Nb)</th>
<th>%Mo</th>
<th>%N</th>
</tr>
</thead>
<tbody>
<tr>
<td>439</td>
<td>0.01</td>
<td>17</td>
<td>~ 0.3</td>
<td>-</td>
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</tr>
<tr>
<td>444</td>
<td>0.01</td>
<td>18</td>
<td>~ 0.4</td>
<td>~ 2</td>
<td>0.01</td>
</tr>
</tbody>
</table>
### MECHANICAL PROPERTIES

<table>
<thead>
<tr>
<th>Grade</th>
<th>C</th>
<th>Cr</th>
<th>Mn</th>
<th>Ni</th>
<th>Cu</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>J204Cu (UNS S20430)</td>
<td>≤ 0.1</td>
<td>16.0-17.5</td>
<td>6.5-9.0</td>
<td>1.5-3.5</td>
<td>2.0-4.0</td>
<td>0.1-0.2</td>
</tr>
</tbody>
</table>

#### REQUIREMENT

**HIGH STRENGTH & HIGH FORMABILITY**

**APPLICATIONS**

DEEP DRAWN KITCHENWARE, SINKS, ELEVATORS, AUTOMOTIVE HOSE CLAMPS etc.

**SWITCH TO**

204Cu

---

**Values, MPa**

- **Y.S.**
  - 304
  - J204Cu

- **T.S.**
  - 304
  - J204Cu

**% Elongation**

- 304
- J204Cu
DRAWABILITY OF 204Cu:

![Graph showing the relationship between H_max/D and r_p/D](image1)

![Graph showing the relationship between Drawing height (h/l) and r_c/l](image2)
APPLICATIONS OF 204Cu

**Catering and food processing:** Deep drawn kitchenware, cookware, milk cans

**Consumer durables:** Toasters, microwave ovens & washing machines outer body parts, mobile case/parts

**Architecture, building and construction:** Handrails for staircase elevators, sinks

**Transport (Automotive):** Hose clamps, safety belt anchors

---

**SINKS**

**ELEVATORS**
# REQUIREMENT

<table>
<thead>
<tr>
<th>HIGH STRENGTH &amp; SUPERIOR CORROSION RESISTANCE</th>
<th>SWITCH TO LEAN DUPLEX STAINLESS STEEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade</td>
<td>C</td>
</tr>
<tr>
<td>Low Ni Duplex</td>
<td>2101</td>
</tr>
<tr>
<td>Ni Free Duplex</td>
<td>0.03</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test Media (Boiling)</th>
<th>Duplex Ni Free</th>
<th>Duplex Low Ni</th>
<th>304</th>
<th>316L</th>
</tr>
</thead>
<tbody>
<tr>
<td>1% Oxalic Acid</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>5% Acetic + 5% Formic</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>50% Nitric</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>B</td>
</tr>
<tr>
<td>1% H₂SO₄</td>
<td>B</td>
<td>B</td>
<td>E</td>
<td>C</td>
</tr>
<tr>
<td>5% H₂SO₄ + 20% (NH₄)₂SO₄</td>
<td>B</td>
<td>B</td>
<td>E</td>
<td>D</td>
</tr>
</tbody>
</table>

- A < 0.1 mmpy
- B - 0.1-1.0 mmpy
- C - 1-3 mmpy
- D - 3-10 mmpy
- E > 10 mmpy

IT IS PERFECTLY FEASIBLE TO SWITCH TO MORE COST EFFECTIVE GRADES WITH HIGH FUNCTIONALITY
**Conclusion:**

- Continuous evolution of new attractive grades based on metallurgical concepts from interstitial free to high interstitial grades.
- Trend towards leaner alloys with higher strength & enhanced formability for material conservation.
- Thrust on controlled rolling & accelerated cooling to avoid expensive heat treatment.