Titanium Clad Steel –
Hot Working Considerations & Applications

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by Stéphane PAULY
SECTION 1

NOBELCLAD & EXPLOSION CLADDING PROCESS

TI CLAD – HOT WORKING CONSIDERATIONS

• Effects of Time/Temperature
• Proper Hot Working Procedures

APPLICATIONS & CASE STUDIES
DMC - A GLOBAL COMPANY

Headquarters in Boulder, Colorado, USA

400 people worldwide

In 2013: 209 M$

NASDAQ: « BOOM »

In 2013: 119 M$
NOBELCLAD CAPABILITIES

Cladder: 1 to 30 mm
Base: 1 to 500 mm

50 T
50 m²
13 m max
5 m max

Ti Clad plates for autoclaves
(9m x 2m x 140 mm)

Ti clad tubesheets
(diam 2,3 m x 400 mm)
Typical clad materials used:
- Stainless steel (410S, 316L, 347, 904L…)
- Ni alloys (625, 825, 59, C276…)
- Copper and Cu-Ni-alloys
- Monel 400
- Duplex 2205, 2207
- Aluminium and Al alloys
- Titanium, Zirconium, Tantalum

Typical base materials
- Carbon steel (A 516, 533, 537,…)
- Cr-Mo & Cr-Mo-V (A 387, A 542,…)
- Stainless steels (316L, DUPLEX)
- API 5L / DNV pipe grades

Plates Or forgings
EXPLOSION CLAD PRODUCTS

**Transition joints**
Structural & Electrical bimetals

**Clad plates, heads, tubesheets**
Reactors, hydrotreaters, heat exchangers...

50 years in explosion welding technology

Pressure
Corrosion
EXPLOSION CLAD MARKETS

- Armouring
- Shipbuilding
- Railway
- Electrochemical processing
  - Chlorine cells
- Hydrometallurgy
  - Aluminum
  - Nickel
  - Magnesium

- Energy
  - Upstream downstream Oil and Gas
  - Power Generation
  - Coal Gasification
  - LNG plants
  - Alternative (ITER, solar)

- Chemical & Petrochemical Industry
- Refrigeration
- Steel mills
EXPLOSION CLADDING INTERFACE

- Solid state welding process by the AWS & EN ISO 4063
- Interface similar to FW (atomic sharing bond)
  - Pressure generated by the chock wave
  - Heat generated by displacement and cladding angle
- Jet assures pure and clean surfaces for the welding
- Possible to weld similar and dissimilar metals

Interface ≈ 200nm
INTERFACE - SHEAR PROPERTIES

Typical shear strength:

- Stainless and nickel alloy clad: typically: > 400 MPa
- Lower strength CRA’s (Cu alloys, Ti, Zr): > 250 Mpa

FIG. 1 Shear Test Specimen
**SUMMARY OF EXPLOSION CLAD ATTRIBUTES**

- DETACLAD® process is reliable: 0.005% rejectable area of production area
- Solid state welding process that does not modify:
  - Corrosion properties of cladding metal are conserved (no dilution, No HAZ)
  - Base metal properties unchanged.
- Virtually any metal combination can be welded
  - Similar alloys: Stainless Steel onto Steel
  - Dissimilar alloys: Ti or Al onto Steel
- Plates & forgings can be cladded
- Detaclad® will not disbond when fabricated by proper thermal and mechanical procedures
- Flexible is sizes and quantities
- Low cost and high value for many metal types and thicknesses
TI CLAD – HOT WORKING CONSIDERATIONS

- Effects of Time/Temperature
- Proper Hot Working Procedures
Titanium Clad Steel have seen expanded application over the past 40 Years

- Equipment size
- Operating Temperatures
- Operating Pressures

Increased Wall Thickness

….. Tendency toward Hot Forming operations

=> After hot working has the bond been degraded?
Typical hot working conditions:

- Temperature: 400 – 700 °C
- Time: depends on carbon steel thickness (ASME)

**Expectations:**

Exposure to elevated temperatures may transform the EXW interface to intermetallic layer and the interface properties will be degraded.

\[\text{TiFe: } 400-1317°C\]

\[\text{TiFe}_2: 400-1427°C\]
**INVESTIGATION PLAN**

**TABLE 2: Time - Temperature Test Matrix**

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<thead>
<tr>
<th>Time</th>
<th>500</th>
<th>600</th>
<th>650</th>
<th>700</th>
<th>800</th>
<th>900</th>
<th>950</th>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Ti Zr Ti Zr Ti Zr Ti Zr Ti Zr ZR</td>
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<tr>
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<td></td>
</tr>
<tr>
<td>20</td>
<td>Ti Ti Ti Ti Ti Ti Ti Ti</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
</tr>
</tbody>
</table>

*complete set of:*

- Shear tests according to B898
- Microscopic observations
SHEAR STRENGTH EVOLUTION OF TITANIUM-STEEL CLAD

Shear Strength (Mpa)

Time at Temperature (hrs)

As-Clad

500 - 600 °C

650 °C

700 °C

800 °C

900 °C

950 °C
LARSON-MILLER PARAMETER TITANIUM – STEEL CLAD

![Graph showing Larson-Miller Parameter vs. Stress (Mpa). The graph includes a scatter plot with data points and a trend line. The x-axis represents the Larson-Miller Parameter (p = T*(20+log(t))/1000), and the y-axis represents Stress (Mpa).]
BOND ZONE STRUCTURE MODIFICATIONS

- **Over heat area**
- **Recrystallization area**
- **No modifications**

Temperature (°F/°C):
- 1500 / 815
- 1400 / 760
- 1300 / 704
- 1200 / 648
- 1100 / 598
- 1000 / 537

Time (h):
- 0
- 2
- 4
- 6
- 8
- 10
- 12
- 14
- 16
- 18
- 20

A DMC Company
Hot Working Procedures Must Ensure Compliant:
- Formed Shape
- Base Metal Mechanical Properties
- Cladding Metal Corrosion Properties
- Clad Interface Properties

Optimum temperature range for Hot Working Reactive Metal Clad is between 600°C – 700°C
- Avoid unacceptable degradation of interface properties
- Reduce forming loads (decrease of base metal yield strength)
- Below steel lower critical temperature (Minimize changes to base metal structure and mechanical properties)
APPLICATIONS & CASE STUDIES
About 150 Ti & Zr -Steel clad heads formed:

- 80% are 2:1 Elliptical Heads
- 10% Full Hemispherical Heads
- 10% Segmental Construction
CASE HISTORY – TI GR 11 CLAD HEAD

- 4 Hemispherical Heads
  - Head ID: 1686mm (66.4”) Clad Inside
  - Clad: SB265-11, 4.8mm (0.188”)
  - Base: SA516-70, 68mm (2.69”)
  - Single Piece Construction

- Press Formed at ~675°C (1250°F)

- Post form UT: No bond separation

- Shear strength >140mpa
CASE HISTORY – TI GR 17 CLAD HEAD

- 6 Elliptical Heads 2:1
  - Head ID: 4300mm (169”) Clad Inside
  - Clad: SB265-17, 9mm (0.354”)
  - Base: SA516-70, 100mm (4.0”)
  - Segmental Construction, crown and 8 petals

- Press Formed at ~650°C (1200°F)

- No disbonding

- Shear >140MPa
SEGMENTAL TI GR 1 CLAD HEAD
THANK YOU FOR YOUR ATTENTION

Visit us on: www.nobelclad.com