Using Non-standard Materials For Couplings On Special Turbomachinery Applications

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Presenter Bios

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Jack Xu has a B.S. degree (Thermal Power Engineering) from Tsinghua University, and a master degree (Fluid Mechanical) from Shanghai Jiaotong University. Tsinghai and Shanghai Jiaotong Universities are famous engineering universities in China.
Flexible couplings are a critical component in turbo-machinery train. It is a challenge and very important for coupling designers to select suitable materials for special turbo-machinery applications. The non-standard materials addressed here are for couplings operating in environments such as:

1) Corrosion (Stress, Pitting, Hydrogen Embrittlement, Chloride, etc.)
2) Spark Resistant
3) Low Temperature
4) Titanium spacer on sensitive compressor for rotor-dynamic solutions

By joint research with compressor OEMs and coupling vendors, this technical brief intends to find the best materials for the applications where working conditions or rotor dynamic concerns dictate their use.
Stress Corrosion Cracking

- Stress corrosion cracking (SCC) is the combined action of static stress and corrosion leading to cracking or embrittlement.
- When metal is stressed in corrosive environments, the damage usually begins at a corrosion pit from transgranular cracks.
- SCC failure occurs under:
  - SCC Susceptible metal
  - Presence of halide ions (generally chloride)
  - High tensile stresses from load, misalignment or alloy processing
  - Temperatures in excess of about 120°F (49°C)

Transgranular cracking in an austenitic SS U-bend specimen exposed for 8 days to boiling 42% MgCl2 vapors. Etchant, Glyceremia. (70X)
Stress Corrosion Cracking

- Classic indicator of susceptibility to chloride-ion SCC is the boiling 42% magnesium chloride (MgCl₂) test as left
- The test shows that:
  - Series 300 stainless steel (SS) is susceptible to cracking
  - The alloys containing more than 45% nickel are immune to chloride stress cracking (CSC)
  - 15-5PH (3.5~5.5% Ni) is good for CSC as well
  - Duplex (austenitic-ferritic) SS is similar as the higher Ni Series 300, but it seems have good SCC performance in sea water

* AISI - American Iron and Steel Institute

Cracking susceptibility of different Nickel content (Boiling 42% MgCl₂)
* from Website of Special Metals Corporation
Pitting Corrosion In Chloride Solution

- Pitting corrosion is main corrosion type in the environmental condition
- Higher levels of chloride might cause pitting corrosion for ASTM304 austenitic SS as left
- Scanning electron microscopy figure shows the pitting corrosion results exposed at different periods in Chinese Xisha Islands
  - Scale: 50 μm
- Better machining surface precision will improve the pitting corrosion resistance

*ASTM - American Society of Testing Materials*
Hydrogen Embrittledment

- Hydrogen Embrittledment (HE): Metals become brittle and fracture due to the introduction and diffusion of hydrogen
  - Reduce metal's ductility, toughness, and tensile strength, even open hydrogen-induced cracks
  - Can occur anywhere the metal contacts with atomic or molecular hydrogen during manufacturing or operating
  - Normal experienced in relatively high strength steels under static load, roughly above 1000 MPa

- HE major mechanisms are:
  - Hydride-induced Embrittledment
  - Hydrogen Enhanced Decohesion (HEDE)
  - Hydrogen Enhanced Localized Plasticity (HELP)
Sulfide Stress Cracking

- Sulfide Stress Cracking (SSC) is a form of HE related with hydrogen sulfide (H2S)
- Susceptible alloys, especially steels, react with H2S forming metal sulfides and atomic hydrogen as corrosion byproducts
- Atomic hydrogen either combines to H2 at the metal surface or diffuses into the metal matrix
- SSC has special importance in oil & gas industry, as the materials being processed (natural gas & crude oil) often contain H2S
- Equipment that contacts with H2S can specify material as below:
  - NACE MR0175/ISO 15156-1 for oil and gas production environments
  - NACE MR0103 for oil and gas refining environments
ASTM 304 - Corrosion Environment

- ASTM 304 is used in many HP diaphragm and disc couplings because of its good mechanical properties
- It has good resistance to a wide range of corrosion environments
- Increasing chromium level can improve sulfidation resistance

Disadvantage:
- Exhibiting a high susceptible to SCC and HE
  - Raising temperature can increase both SCC and HE in corrosive environments
  - Not recommended for exposure to marine or salt water applications, particularly at high temperatures
Failed ASTM304 Diaphragm in chlorine environment

For high chloride conditions, the suggestion can be:

- Specified following material:
  - Inconel, 15-5 PH or Monel

- Special coatings:
  - PTFE based coatings like Xylan
  - Other coating like Sermetal
Inconel For Chloride Corrosion

- SCC can result in fatigue failure of coupling flex elements
- Some end users only accept Inconel, Monel or 15-5 PH materials because ASTM 300/400 SS is susceptible to SCC
- Inconel is sometimes used for HP couplings at petrochemical applications because of its high strength and corrosion resistance
  - 718 Inconel is high-strength, excellent corrosion resistance nickel chromium alloy used at -423~1300°F (-253~704°C), and was used in chlorine applications for critical equipment successfully until 1990
  - 625 Inconel is presently using for some offshore platform disc couplings due to better crevice corrosion resistance
Martensitic Precipitation-hardening SS Diaphragm

- 15-5 PH/17-4 PH was selected for HP couplings as a replacement of Inconel because of its higher strength and relatively lower cost.
- 15-5 PH/17-4 PH has good all-around corrosion resistance and good material properties in all applications.
  - Much greater resistance to SCC compared to 300 series.
  - Accepted for H2S & chlorine without coatings.
- 15-5 PH/17-4 PH diaphragms are also a good choice where AISI 4340 with coating has environmental concerns.
- Shot peening can improve corrosion resistance of the flexible diaphragm since SCC can't occur in the area with compressive stress.
Spark Resistant Material

API 671 4th Edition - Coupling Guard Material

H.2.9 If specified, the guard shall be fabricated from spark-resistant material, such as aluminum, aluminum alloys, copper or copper-based alloys. A description of the materials of construction shall be submitted to the purchaser for approval.

API 610 11th Edition - Bearing Housing and Coupling Guard Material

6.10.2.6 ...The seals and deflectors shall be made of spark-resistant materials. The design of the seals and deflectors shall effectively retain oil in the housing and prevent entry of foreign material into the housing.

NOTE Many users consider pure Aluminum, Aluminum Alloys with a max. content of 2% Magnesium or 0.2% Copper, all Copper, and Copper-based Alloys (e.g. Brass, Bronze) to be spark-resistant. However, the standards, such as EN 13463-1, might not allow Aluminum or non-metallic materials within potentially explosive atmospheres.

7.2.13 Each coupling shall have a coupling guard that is removable without disturbing the coupled elements. Each coupling guard shall meet the following requirements: ...

d) be constructed of steel, brass, aluminum or non-metallic (polymer) materials, as suitable;

7.2.14 If specified, coupling guards shall be constructed of an agreed spark-resistant material (see 6.10.2.6, note).

7.2.15 If specified for coupling guards with potentially explosive atmospheres, an "ignition hazard assessment" (risk analysis) in accordance with EN 13463-1 shall be conducted and a suitable report provided.
Spark Resistant Material

Spark resistant concepts for turbo-machinery HP couplings?

- Standard EN 13463-1: 2009
  Non-electrical equipment for use in potentially explosive atmospheres.
- Only using spark resistant material (SRM) for HP coupling flex element & the guard doesn’t make sense while other components (coupling spacer & fasteners, compressor shafts, mechanical seals, probes...) are not SRM
- HP coupling’s 100m/s projectiles can spark against any SRM guard etc.
- Equipment is spark resistant only if:
  - Moderate energy collisions (≤ 15 m/s) occur where SRM is used in all components
  - Low energy collisions (≤ 1 m/s) occur where steel is not used with Aluminum or Titanium
Coupling with over-torque spacer shear section

Spark Resistant Material

Bronze Bearing Under The Groove
BSB23 Non-sparking Overload Collar

- BSB23 is a copper based high strength alloy with spark resistant properties
- Used for spark resistant overload collars in some couplings
  - Allows drive to be maintained by contact with the overload holes in the event of flex element failure

Note: ATEX cert only specifies that the coupling is non-sparking under normal operating conditions. It does not account for coupling failure.
Low Temperatures

- Low temperatures cause materials to be brittle and potentially crack.
- Failure happens at the stress far below than yield strength for ferritic steels.
- Ferritic materials have generally low impact values at the lower temperature, prone to becoming brittle.
  - Requiring a change to austenitic material or special low temperature steels.
  - The impact values of ASTM304&316 at -196°C is only 9 to 24% lower than the values at 0°C.
- Charpy V-notch test is to measure ductility (AK) at low temperatures to determine material acceptability.
Low Temperatures

- **AISI 4340** is the material specified for use at operating temperatures down to -80°C.
- Material of whole coupling left is AISI 4340 for very low temperature wind tunnel application, except:
  - Diaphragms (15-5 PH)
  - Helicoils (SS)
- **ASTM A350 LF2** normalised carbon steel was used for pump applications down to -54°C
Couplings Lateral Critical Speed (LCS)

Coupling lateral natural frequency shall be at least 1.5 times of the highest specified operating speed.
Couplings Overhang Moment

\[ \frac{1}{2} \text{ weight} \times (D-CG)^x = \text{Overhung Moment} \]
Overhang moment mainly influences 2\textsuperscript{nd} lateral critical speed.
\( X = 2, 3, \text{ or } ? \)
Train Lateral & Torsional Critical Speeds

1st Torsional

1st Lateral

Operating Speed

Minimum 10% away from operating speed per API-617

2nd Lateral

2nd Torsional

RPM
Titanium spacers are sometimes selected for rotor dynamic reasons

- API-617 requires a compressor train to operate at least 10% away from all critical speeds
- The 2nd lateral being to close the operating speed is often the reason for the substitution
- Increasing the spacer diameter to make the coupling stiffer and/or making the spacer thicker for torsional issues adds too much weight
- Titanium offers a good combination of high lateral stiffness and light weight

Case for the retrofitting to Titanium spacer coupling:

- 5432HP@18,422rpm DBSE 750mm coupling for a compressor on an oil platform
- Significant vibration problems on existing coupling because the steel spacer was too heavy
- The compressor required very low overhung weight and moment
- High speed and relative long length was a difficult combination

The Titanium spacer coupling ran well after retrofitting
LCS Analysis of Titanium Spacer

Lateral critical speed: 29,459 CPM (3D FEA)

Meet API 671 (4th ED) 8.12.2: The lateral natural frequency (Nc) of the coupling between and including the flex elements shall be at least 1.5 times the highest specified operating speed by 3D FEA
Titanium Coupling

Mostly Titanium spacer only, rarely Titanium diaphragm
Titanium Coupling

- Pure Titanium and Titanium alloys offer excellent resistant to many commonly corrosive media
  - Resistance to HE and hydriding is poor
- Besides high strength and corrosion resistant, Titanium is good for aircraft as the hub left because of its light weight:
  - Spline further reduce the weight
- Titanium is expensive because of very limited supply

Titanium Hub - Aircraft Application
## Summary

- SCC resistance for coupling flex element material:

<table>
<thead>
<tr>
<th>Coupling Flex Element Material</th>
<th>SCC Resistance</th>
<th>Price</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM 304</td>
<td>Susceptible</td>
<td>Cheap</td>
<td>Not good for chloride conditions</td>
</tr>
<tr>
<td>Duplex SS</td>
<td>Susceptible</td>
<td>Moderate</td>
<td>Susceptible to HE</td>
</tr>
<tr>
<td>15-5 PH</td>
<td>Immune</td>
<td>Expensive</td>
<td>Outstanding combination</td>
</tr>
<tr>
<td>Inconel</td>
<td>Immune</td>
<td>Very Expensive</td>
<td>Hard to Machine</td>
</tr>
<tr>
<td>Titanium</td>
<td>Immune</td>
<td>Very Expensive</td>
<td>Poor Resistance to HE</td>
</tr>
</tbody>
</table>

- Only SRM flex element and the guard for HP coupling does not help at failure condition because of high energy collision
- AISI 4340 is good for very low temperature applications
- Titanium coupling is used as the last resort for rotor dynamic reason

### Questions?