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Session Title: Challenges In Resourcing And Fabrication Of High Thickness Super Duplex Stainless Steels – The Most Widely Used CRA For HPHT Services

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Presenter Title: Senior Manager

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Presenter Company: Sembcorp Marine (SCM), established in Singapore and strategically located in Singapore, Indonesia, the United Kingdom and in Brazil, operates shipyards known as SMIY, and provides innovative engineering solutions to the global offshore, marine and energy industries. Drawing upon more than 50 years of track record and an extensive network of facilities and expertise, the Group focuses on four key capabilities, namely, Rigs & Floaters; Repairs & Upgrades; Offshore Platforms and Specialized Shipbuilding.

Challenges In Resourcing And Fabrication Of High Thickness Super Duplex Stainless Steels – The Most Widely Used CRA For HPHT Services

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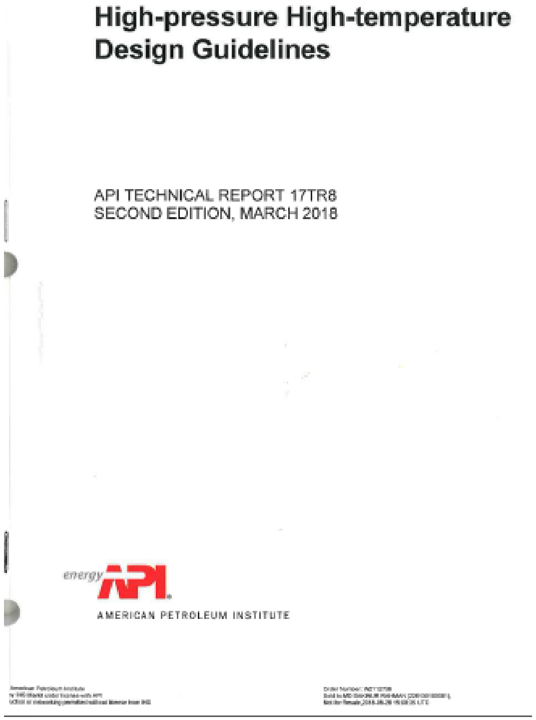
High Pressure High Temperature (HPHT) Well Attributes and Environments:

- Congenital high pressure hydrocarbons in elevated temperature.
- As per API Technical Report 17TR8 (2018 Edition), definition of HPHT is: above 15,000 psi (1034 bar) and 350°F (177°C);
- HPHT Wells Should be considered as sour source;
- Could contain C02; and,
- Other chemicals, such as, mercaptan, nitrogen (N2), mercury, radon, arsine, sand particles, etc.

Challenges of Various Phases in HPHT Field Developments:

- **Field Characterization:** Highly challenging in field characterization, at a vertical depth of 4 Km or more below sea level, **geologically Jurassic or Triassic aged reservoirs.**
- **Drilling:** Each well may pose new, different and unknown attributes
- **Challenges in upstream field development:** Needs appropriate technology, equipment, software, controls and adequate reliable data – are these available?
- **Challenges in downstream (fixed and floating) facility development:**
  - Maintain HPHT design attributes in the facility
  - Ensure operational reliability throughout the design life.
  - Source the right materials, perform fabrication, inspection, test, verification & commissioning;
- **Challenges during production phase, facility operation and maintenance.**


High-pressure High-temperature Design Guidelines

API TECHNICAL REPORT 17TR8
SECOND EDITION, MARCH 2018

energy API
AMERICAN PETROLEUM INSTITUTE

Challenges In Resourcing And Fabrication Of High Thickness Super Duplex Stainless Steels – The Most Widely Used CRA For HPHT Services

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- **HPHT Well – Common Scenarios**
  - **HPHT Wells Environments → Load Scenarios:**
  - Internal high pressure in elevated operating temperature;
  - External environmental pressure with various dynamic loading with fatigue attributes;
  - Elevated pressure and temperature induced additional loadings.
  - **HPHT Wells Environments → Corrosion Potential:**
  - Presence of internal corrosive agents, such as, CO2, H2S, Temperature, Organic Acids, Oxygen, Elemental Sulfur, Mercury, Production Chemicals;
  - Sand erosion
  - External corrosion – external marine atmospheric environments
  - Corrosion under insulations (CUI).
- **Subsea Controls:**
  - **Upstream Regulation:** No regulation in the upstream, then the HPHT well fluids will be transported up to the platform, piping and the associated equipment are to be rated against HPHT.
- **So, in HPHT Field Developments, Challenges are at all Phases – similar or different, specific or common, and are moving onwards from one phase to next phase.**

Despite all these challenges, why go for HPHT Wells?

- The simple answer is: Mankind needs more and more energy. Nothing can be done without energy!
- The US Energy Information Agency (EIA) predicts that fossil fuels will still supply nearly 80% of US energy demand in 2050. Likewise, EIA predicts that a growing global middle class is expected to increase global energy demand 28% by 2040, and that fossil fuels will still meet 77% of that demand [WO, April'2018].
- On the other hand, easier targets are getting less and less, so the search for hydrocarbons is being driven to geologically challenging and environmentally aggressive locations including ultra-deep water with high pressure and high temperature (HPHT) bottom hole well conditions.

Benefits of HPHT Wells:

- **High Pressure and High Temperature – means, dense and more hydrocarbons, which means, more energy.**

Challenges In Resourcing And Fabrication Of High Thickness Super Duplex Stainless Steels – The Most Widely Used CRA For HPHT Services

HPHT Wells → Should be considered as Sour Sources:

- **API Technical Report 17TR8, Section 6.2.2**: HPHT wells should be considered as **Sour** with the possibility that the H_2S content may increase over the life of the well.
- **Sour Service:** Sour service condition contains H_2S and can cause cracking of materials by mechanisms that include sulfide stress cracking (SSC), stress oriented hydrogen induced cracking (SOHIC) and galvanically induced hydrogen stress cracking (GIHSC).
- **Sour Service Application - H_2S Concentration:**
  - Annex B, Table B.1 of API Technical Report 17TR8: the concentration of H_2S (in ppm) in the gas phase -

Table B.1 – H_2S Concentration in ppm to Equal 0.05 psia Partial Pressure at Standard Rated Working Pressures

Rated Working Pressure	10 ksi	15 ksi	20 ksi	25 ksi	30 ksi
H_2S concentration (ppm)*	5	3.3	2.5	2	1.7
* These calculations are based on linear gas laws.					

Materials – the Common Challenge at Each Phase of HPHT Well development:

- **Sour Service Condition – affects materials selection highly:**
  - Materials shall be compatible to Sour Service, loads, hostility of the interacting HPHT conditions and aggressiveness of the internal and external environments for the entire designed life.
  - For offshore installations, access for repair and maintenance can be limited and costly. Design and Materials selection shall consider this.
  - Need high thick materials, which have inherent issues like, heavy weight, handling difficulties during welding/fabrication/assembly, long fabrication time, welding difficulties, possibility of inhomogeneous property across the material, as well as, weld thickness;
  - Finally, cost and economics.

Candidate Materials for HPHT Environments:

- **Codes and Standards**
  - **ISO 21457: 'Petroleum, Petrochemical and Natural Gas Industries - Materials Selection and Corrosion Control for Oil and Gas Production Systems'**
  - **NACE MR0175/ISO 15156: 'Petroleum and natural gas industries – Materials for use in H2S-containing Environments in oil and gas production**' –
    - Part 1: General principles for selection of cracking-resistant materials;
    - Part 2: Cracking-resistant carbon and low alloy steels, and the use of cast irons;
    - Part 3: Cracking-resistant CRAs (corrosion resistant alloys) and other alloys.
- **Candidate Materials**
  - A variety of high grade **Corrosion Resistant Alloys (CRAs)** have been developed across the industry.
  - **CRA has been defined as: alloy intended to be resistant to general and localized corrosion by oilfield environments that are corrosive to carbon steels.** ISO 21457 and ISO 15156-1 included the materials such as stainless steel with minimum 11.5% (mass fraction) Cr, and nickel, cobalt and titanium base alloys in the CRA list. Other ISO standards can have other definitions.

Challenges In Resourcing And Fabrication Of High Thickness Super Duplex Stainless Steels – The Most Widely Used CRA For HPHT Services

❑ Materials Selection from Candidate Materials for HPHT Environments:

- **ISO 21457, Table 4** specifies recommended materials for hydrocarbon production and process systems as summarized in the **Table-1** (right) with their typical strength:
- For HP and HT application, apart from corrosion resistance, the other most important criteria that the nominated CRA shall have: **high strength at the design temperature**.
- **Chemical Composition of High Strength CRAs: Below T**able presents the chemical compositions of 3 potential high strength candidate CRAs (Type 25 Cr, Type 22 Cr and Type 13 Steels) for comparison:

Table-1: Recommended CRAs and typical strengths

CRA (Material) Type	Yield Strength (Typical), MPa (Ksi)	Tensile Strength (Typical), MPa (Ksi)
Type 316	205 (30)	515 (75)
Type 316L	170 (25)	480 (70)
Type 22Cr	450 (65)	620 (90)
Type 25Cr (UNS S32760)	550 (80)	750 (108)
Type 6Mo	303 (44)	650 (94)
Type 13Cr	620 (90) (intermediate temper)	825 (120) (intermediate temper)
Type 625 (UNS N06625)	415 (60)	830 (120)

Type	Name	PREN	C	Cr	Ni	Mn	Si	Mo	N	Cu	W	P	S	Ti	V
Type 25 Cr	UNS S32760 (2507)	40 to 46	0.03	24.0 to 26.0	6.00 to 8.00	1.00	1.00	3.00 to 4.00	0.20 to 0.30	0.50 to 1.00	0.50 to 1.00	0.03	0.01		
Type 22 Cr	UNS S31803 (2205)	31 to 38	0.03	21.0 to 23.0	4.50 to 6.50	2.00	1.00	2.50 to 3.50	0.08 to 0.20	-	-	0.03	0.02		
Type 13 Cr	UNS S41426		0.03	11.5 to 13.5	4.5 to 6.5	0.5	0.5	1.5 to 3.0	-	-		0.02	0.005	0.01 to 0.5	0.5

- The compositions have been shown in mass fraction (%wt).
- Where a range is shown, it indicates min. to max. mass fraction
- PREN = %Cr + 3.3 (%Mo) + 16 (%N)

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Materials Selection from Candidate Materials for HPHT Environments:

- Type 13Cr and Type 25Cr are the two CRAs having the highest YS - 620 and 550 MPa respectively. The other nearest CRAs are Type 22Cr and Type 625 having YS 450 MPa and 415 MPa respectively.

Corrosion Resistant Alloys (CRAs) – Type 13 Cr:

- **Type 13 Cr** belongs to Martensitic Stainless Steels (MSS) family, contain low chromium (typically, in the range of 12 to 15 %wt.) and high carbon content (typically, in the range of 0.15 to 0.25 %wt.).
- **Weldability:** These are weldable with C= 0.06 or less, with procedures similar to applicable for welding of low-alloy high strength steels. Other grades with higher C than this value are least weldable and specialized procedure is required for welding without cracking.
- **Corrosion resistance** is not as good as other grades of SS.
- **Sour service** is prone to SSC, SOHIC, GIHSC, etc. So, Type 13 Cr , despite their high YS and low cost, these materials are **not an appropriate material HPHT (sour service) flowlines, risers and topsides piping works where welded connections are to be used**.

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❑ Corrosion Resistant Alloys (CRAs) – Type 22 Cr and Type 25 Cr, the Duplex Stainless Steels:

- **Type 22Cr and 25Cr (Duplex Stainless Steels):** These belong to duplex stainless steel (DSS), they exist in two microstructures (ferrite & austenite) at room and working temperatures.
- **Table D.7 of NACE MR 0175/ISO 15156** listed a number of DSS.
- **Field Development:** The amount of piping works in an offshore platform and the associated flowlines, manifolds, risers etc. can vary widely depending on platform size, water depth, flowline layout and architecture, reservoir locations etc.
- **HPHT Developments:** HPHT field development with large to medium sized platform of 19 to 20 thousand tons of steels, having a peak production capacity of 400 to 500 million standard cubic feet per day will have approximately **67 Km of piping** of different sizes, **75 thousand pieces of fittings**, **85.5 thousand of butt welded joints** and **960 nos. of hub joints (Sembcorp Marine Study under Reference [12])**.
- **Type 25 Cr – Most Widely Used SDSS**: For this huge piping works of HPHT Platforms, Type 25 Cr is the most widely used CRA among all the listed CRAs. **According to Sembcorp Marine's study (Reference [12])**, a HPHT Platform of large size, **SDSS will contain approximately 55.27% of Total CRA Pipes and 63.18% of Total CRA Fittings**.

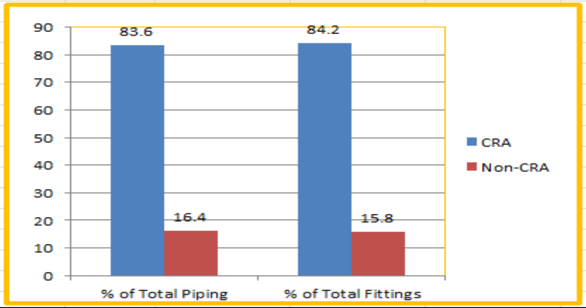

Fig. 1: Usage of CRAs and Non-CRAs in HPHT Platforms

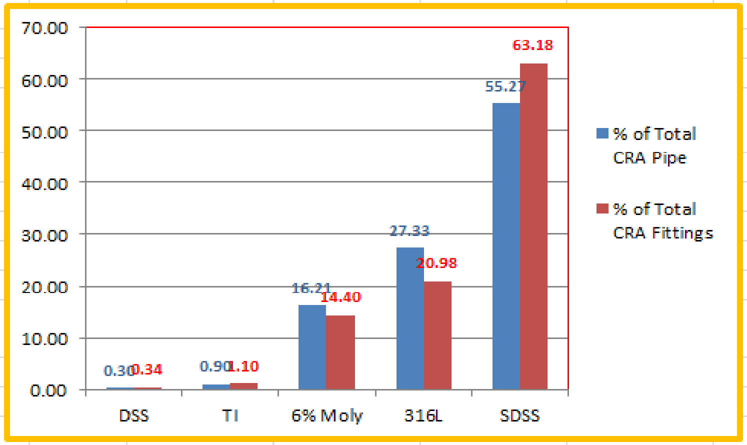

Fig. 2: Application of SDSS (Type 25 Cr) in HPHT Platforms (% of total CRA Pipes and Fittings)

❑ Super Duplex Stainless Steels, Type 25 Cr – The Most Widely Used CRA for HPHT Service:

❑ Salient Features of Super Duplex Stainless Steels:

- **Mechanical Properties:**
  - DSS/SDSS have exceptional mechanical properties.
  - Room temperature YS in solution annealed condition is more than the double of standard austenitic SS (not alloyed with nitrogen).
  - YS is even higher than that of **nickel base alloys like Alloy 625**.
- **Comparison of YS** can be as follows:
  - SDSS (S32760) to SS (S31603/316L) is: **55 ksi (380 MPa)** [80 ksi (550 MPa) – 25 ksi (170 MPa)]
  - SDSS (S32760) to DSS (S31803) is: **15 ksi (100 MPa)** [80 ksi (550 MPa) – 65 ksi (450 MPa)]
  - SDSS (S32760) to Alloy 625 (N06625) is: **20 ksi (135 MPa)** [80 ksi (550 MPa) – 60 ksi (415 MPa)]
- **Key Advantage:** This is one of the most important factors and key advantages that the designer exploit to select this SDSS for HPHT applications to keep the wall thickness within manageable conditions.
- **Ductility & Toughness:** DSS/SDSS exhibits good ductility and toughness, and retain it even at low ambient temperatures, for example, at -40 ^{o}C/F. **In general, DSS/SDSS is having the ductility and toughness** lower than those of austenitic stainless steels, and higher than carbon and ferritic stainless steels.
- Cost: DSS is more expensive (but well below than Ni-base alloy like Alloy 625) than that of SS. This is due to the cost of processing the as-cast DSS to finished product (plate, sheet or tubular).
- May be used in place of some Ni-base alloys in mildly aggressive environments at a fraction of the material cost.

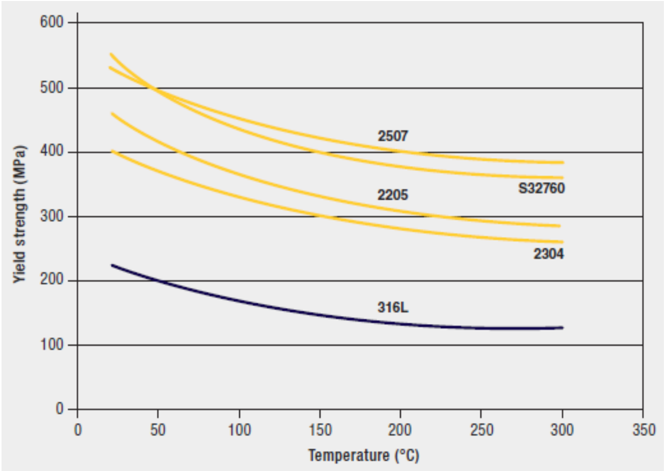

Fig. 3: Comparison of typical yield strength of duplex stainless steels and Type 316L between room temperatures and 300^{o}C (Curtsey: IMOA – Practical Guidelines for the Fabrication of Duplex Stainless Steels)

- **DSS/SDSS for SCC and Pitting Corrosions:** In many applications, where SCC and pitting corrosions are concerns, DSSs have now been substituted for austenitic alloys.

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- **However, Duplex/Super Duplex Stainless Steels have a number of limitations, that pose Specific Challenges During Manufacture and Fabrication (Welding):**
  - **Key Limitations**
    - **Precipitations: SDSS/DSS are highly alloying, and morphology of Duplex Stainless Steels Solidification** is significantly complex.
    - A number of precipitation reactions can occur from below approximately 1000°C (1830 °F). All of these precipitation reactions are time and temperature dependent, and **can form in a matter of minutes at the critical temperature (refer to Fig. 4)**.
    - **These include sigma, chi and alpha prime, as well as, chromium nitride. These precipitations embrittle the duplex alloys, and reduce toughness and corrosion resistance significantly**. These are to be avoided during product manufacturing and in Welding.
    - **Sigma Phase:** Sigma phase (approximately FeCr), is a deleterious Cr, Mo rich, on cooling too slowly through the temperature range of 650°C to 1000°C. (RG-P-40]
      - All mill product shall be water quenched as rapidly as possible from the solution annealing temperature to avoid the sigma phase field.

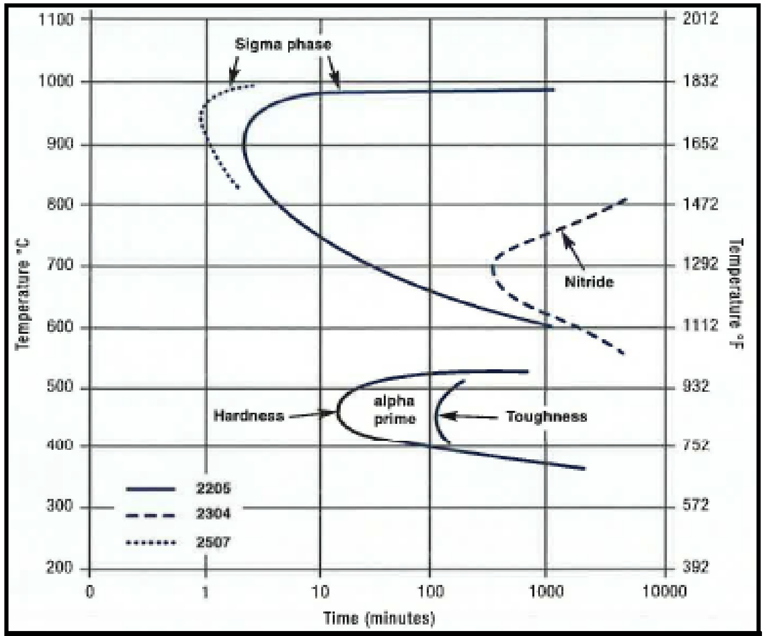

Fig. 4: Isothermal precipitation diagram for 2205 duplex stainless steel, annealed at 1050°C (1920°F). (The sigma phase and nitride precipitation curves for 2507 and 2304, respectively, are shown for comparison) (Curtsey: IMOA – Practical Guidelines for the Fabrication of Duplex Stainless Steels)

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- ❑ **However, Duplex/Super Duplex Stainless Steels have a number of limitations, that pose Specific Challenges During Production and Fabrication:**
  - ❑ **Key Limitations**
    - **Chi Phase:** Chi phase, approximately Fe3CrMo, may form in much smaller quantity in the temperature range of 700°C to 1000°C.
    - **Nitride:** Nitride precipitation reaction occurs upon cooling from solution annealing, due to too slow cooling through the temperature range of 600°C to 900°C. It can be largely or completely avoided in the steel mill by an appropriate (sharp) water quenching from an adequate solution annealing temperature.
    - **Cr, Mo, W:** These alloying elements added to duplex/super duplex stainless steels for certain beneficial purposes, but addition or increase level of Cr, Mo and W tend to accelerate the formation of these precipitates, particularly, the sigma and chi phases.
    - **Ductile-to-brittle Transition:** DSS/SDSS do undergo a ductile-to-brittle transition at low temperature, and as such, they are not suitable for cryogenic temperatures.
    - 425°C (Alpha Prime) Embrittlement: Embrittlement of ferritic phase will happen upon long exposure at 475°C (885 °F). Upper service temperature is thus controlled to avoid Alpha Prime formation. The service temperature is generally limited to -40 °C to 280°C (-40°F to 535°F), although, Codes (ASME B31.3) allowed them to use little higher (refer to Fig. 5)

Grade	ASME Section VIII (Div. 1)	ASME B31.3
S32304	316 (600)	316 (600)
S32101	316 (600) Code Case 2418	NL
S32003	343 (650) Code Case 2503	343 (650) Code Case
S31803 (Note 1)	316 (600)	316 (600)
S31200	316 (600)	NL
S31260	343 (650)	NL
S32550	260 (500)	NL
S32750	316 (600)	316 (600)
S32760	316 (600) Code Case 2245	316 (600)

NOTE NL = not listed
1) S32205 can use the design allowables for S31803 and the material should be dual-certified.

Fig. 5: ASME Code Maximum Allowable Temperatures, °C (°F) (Curtsey: API Technical Report 938-C, Second Edition, April 2011, Use of Duplex Stainless Steels in the Oil Refining Industry)

Challenges In Resourcing And Fabrication Of High Thickness Super Duplex Stainless Steels – The Most Widely Used CRA For HPHT Services

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❑ Super Duplex Stainless Steels, Type 25 Cr – The Most Widely Used CRA for HPHT Service:

❑ Physical Properties of Super Duplex Stainless Steels:

- **Physical Properties** of DSS/SDSS fall in between austenitic stainless steels and carbon steels. Following table shows some of the salient features of physical properties for carbon steel, austenitic and duplex grades:

Grade (UNS No.)	Density (gm/ cm3)	Specific Heat (J/kg K)	Electrical Resistivity (micro Ωm)	Elastic Modulus (GPa)			Coefficient of Thermal Expansion (10^{-6}/K)			Thermal Conductivity (W/m K)		
				20°C	100°C	200°C	100°C	200°C	300°C	20°C	100°C	200°C
Carbon Steel (G10200)	7.64	447	0.10	207			12.1	13.0	--	52	51	49
Type 304 (S30400)	7.98	502	0.73	193	192	183	16.4	16.9	17.3	14.5	16.2	17.8
Type 316 (S31600)	7.98	502	0.75	193			16.0			15		
Type 22 Cr (S31803)	7.80	500	0.80	200	190	180	13.0	13.5	14.0	16.0	17.0	19.0
Type 25 Cr (S32750)	7.75	485	0.80	200	190	180	13.0	13.5	14.0	16.0	16.0	19.0
Type 25 Cr (S32760)	7.80		0.85				12.8			12.9		

- **Low Thermal Expansion:** Duplex stainless steel has low thermal expansion coefficients (that are very close to carbon steels) compared with stainless steels. This has made DSS (compared to austenitic SS) less likely to undergo distortion, and as well as, made **more comfortable to use thin-wall fabrication**.

Challenges In Resourcing And Fabrication Of High Thickness Super Duplex Stainless Steels – The Most Widely Used CRA For HPHT Services

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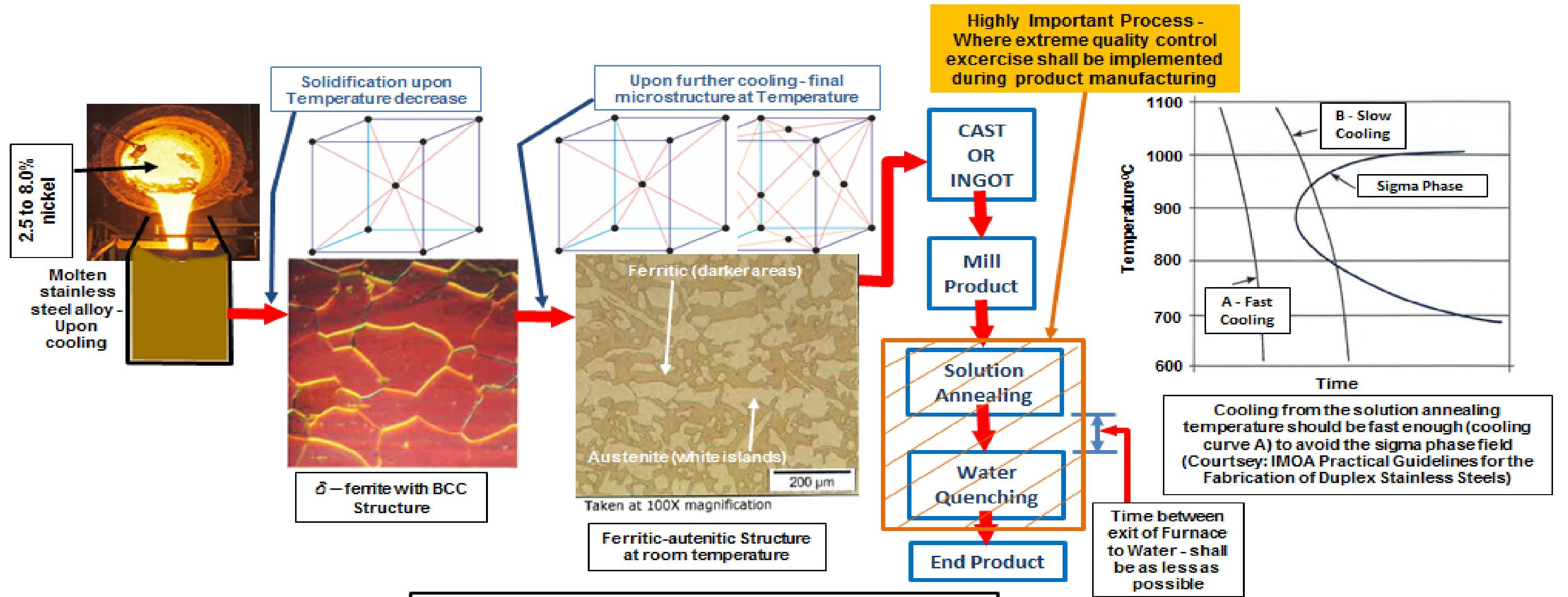
Specific Challenges with Super Duplex Stainless Steels (SDSS) – The Most Widely Used CRA For HPHT Services:

- **Standing at the point of Platform Manufacturer End, Sembcorp Marine faced Two Major Challenges relating to materials and fabrication, that is, (a) Sourcing of Right SDSS at the time of its need, (b) SDSS are very high strength Materials, Fabrication is highly Time Consuming;**
  - **(a) Challenges in Sourcing of Right SDSS:**
  - **Highly Alloyed Type 25 Cr,** Super Duplex Stainless Steels are always considered as extremely long lead items.
  - **Long Manufacturing Schedule Vs Compact EPC Schedule:**
    - EPC Contractor works with the Highly Compact Schedule;
    - On the contrary, it deal with the longest Manufacturing Schedule for SDSS materials.
    - Project specifications and requirements of specific regulations generally fall outside the standard manufacturing process, and translate s to further longer period for delivery.
  - **Scarcity of Responsive and Capable Manufacturer:** Majority of the SDSS Manufacturers are located in Europe, America, Japan and Korea. There are manufacturers elsewhere in other countries, but their track records are not proven. As a result, the search for SDSS materials remain always limited to these countries. Number of such reputed SDSS manufacturer is below 100.
  - **Non-stock:** Generally, the materials of HPHT applications are non-stock items, and require longer period for delivery.
  - **Product Certifications:** EN 10204 Type 3.1 Certifications are the usual requirements for documentation. However, for HPHT applications, the project specification may call for Type 3.2 Certifications, which are to be validated by either the purchaser's authorized inspection representative or the inspector designated by the official regulations. Type 3.2 certification will further add the length of Lead Time.
  - **In a nutshell, sourcing of SDSS Piping Materials is a great challenge:** Sourcing of these (Slide-13) huge quantity of quality SDSS pipes and fittings is a great challenge. **The ultimate goal is to obtain each and every SDSS Materials as defect-free with the desired micro-structure without having detrimental precipitates**.

❑ Specific Challenges with Super Duplex Stainless Steels (SDSS) – The Most Widely Used CRA For HPHT Services:

➢ (a) Challenges in Sourcing of Right SDSS:

- **Ultimate Goals & Quality Gates: Q**uality SDSS product will be the one, which has satisfactorily overcome all the manufacturing limitations mentioned in above slides. SDSS Manufacturing is complex, highly time-bound and quality oriented. As such, the manufacturing process shall be extremely efficient and the quality gates shall be highly robust (below process evolution for illustration).



Evolution of Duplex Stainless Steel

- **Specific Challenges with Super Duplex Stainless Steels (SDSS) – The Most Widely Used CRA For HPHT Services:**
  - **Standing at the Platform Manufacturer End, Sembcorp Marine faced Two Major Challenges relating to materials and fabrication: (a) Sourcing of Right SDSS at the time of its need, (b) Fabrication of SDSS Materials is Highly Time Consuming Process**
  - **(a) Challenges in Sourcing of Right SDSS:**
    - **Histories of Received Products – Non-complying Materials:** Sembcorp Marine received cracked SDSS materials, and also observed material failure upon **Sampling Tests** at site. Due to its highly effective Quality Management System, it identified all these noncomplying materials, and was able to take all corrective actions.
    - Sembcorp Marine's last HPHT Project Specification calls for additional Sampling Tests of all materials having Type 3.1 Certification @ 1% additional random testing over and above the tests required by product specifications or MPS. Below are the details of SDSS material failure:
      - Crack on SDSS Elbows;
      - SDSS Flanges of different sizes failed on Impact Test;
      - LTCS Elbows failed on Impact Test;
      - SDSS Pipes failed on Impact Test;
      - Stud bolts failed to meet the tensile strength;
      - SDSS Flanges failed on Corrosion Test

Specific Challenges with Super Duplex Stainless Steels (SDSS) – The Most Widely Used CRA For HPHT Services:

(a) Challenges in Sourcing of Right SDSS:

- **Materials Failure – Cracks in SDSS Elbows:** Cracks were found in cold formed elbows at the bevel edge, Material Grade is: 3" ASTM A815 UNS S32750, SCH 40S, 90° LR upon receiving at fabrication site. Sembcorp Marine (SMOP -the EPC Contractor) made an analysis for Identification of Cracking Mode by Scanning Electron Microscope in DNV Laboratory. Since, there were a number of such items in one delivery, it might be considered a failure of in the quality system as it crossed all the quality gates.
- Test Result suggested the following:

Location	Observed Morphology	Cracking Mode
#1 – Shining region	Intergranular facets	Brittle cracking mode
#2 – Brown region	Heavily covered with oxides	Oxidized surface
#3 – Green region	Heavily covered with oxides	Opened crack surface showed distinct radial lines indicative of brittle surface

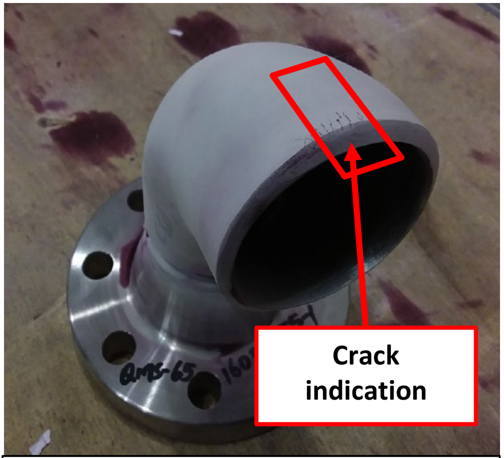


Fig. 6: Crack on the machined bevel edge

Fig. 7: Crack surfaces after opening the crack

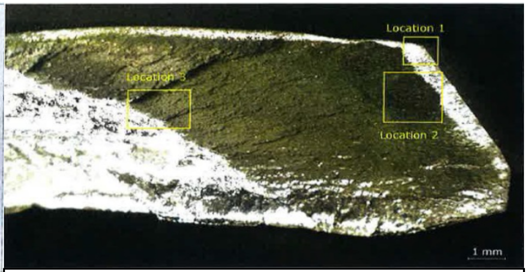


Fig. 8: One side of crack surface after cleaning

> **This presentation is not focused on failure analysis, but this information will initiate thoughts for further study on development of cracks on machined bevel edges of cold formed SDSS elbows upon embrittlement.**

Specific Challenges with Super Duplex Stainless Steels (SDSS) – The Most Widely Used CRA For HPHT Services:

(a) Challenges in Sourcing of Right SDSS:

- **Low Impact Values as recorded in the following cases**
  - SDSS Flanges failed to meet the impact values. While the MTCs show the impact values as high as 121J, some of the samples failed with unexpectedly low values at about 6J. Number of such affected items are in the ranges of hundreds.
  - LTCS Elbows failed to meet the absorbed energy during impact test on random sampling .
  - SDSS Pipes failed to meet the absorbed energy during impact test on random sampling.
- **Stud bolts failed to meet the tensile strength.**
- **Stud bolts failed to hardness requirement.**
- **Pipe found having microstructure with intermetallic compound**

CHARPY V-NOTCH IMPACT TEST RESULTS

Pendulum striking edge : ASTM

Test performed by : Chan / Praithoon

Specimen size (mm)	Location	Test temp. (deg. C)	Individual Value (J)			Average value (J)	Remarks
			(1)	(2)	(3)		
7.5 x 10 x 55	Flange Hub (TH/2)	-46	5	4	4	4	-
10 x 10 x 55	Flange Body (TB/2)	-46	30	23	29	27	-

Note :
- flange hub specimens taken in an axial direction to the bore of the flange (longitudinal).
- chamfer was observed on one corner of the Flange Hub test specimens.

- **Specific Challenges with Super Duplex Stainless Steels (SDSS) – The Most Widely Used CRA For HPHT Services:**

- **Quality Gates** :
  - **A single piece of piping material needs to cross the hurdles of following quality gates:**
    1. **ASTM or API Standard requirements**
    2. **Project Specific requirements**
    3. **NACE MR0175/ISO 15156**
    4. **PMA Requirements for the materials**
    5. **PED Certifications for the Manufacturers with Type 3.1 Certifications for the materials**
    6. **Qualification through Random Sampling Tests**
  - **Important key** point to note that, the above gates will only help to identify the issues, but will not fix the issues, if there is any.
  - **Effectiveness of Quality Gates:** Significant material issues/failures were encountered (as mentioned above) despite the existence of above gates. As the issues were identified at the end part of the Project, these pose critical setback in the delivery. Improvement on the effectiveness of these quality gates may reduce or eliminate these type of challenges.
  - **Replacement of noncomplying materials were the mitigations of these failures, and there** were very time-critical with respect to project delivery.

Challenges In Resourcing And Fabrication Of High Thickness Super Duplex Stainless Steels – The Most Widely Used CRA For HPHT Services

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Specific Challenges with Super Duplex Stainless Steels (SDSS) Fabrication:

- **Standing at the point of Platform Manufacturer End, Sembcorp Marine faced Two Major Challenges relating to materials and fabrication, that is, (a) Sourcing of Right SDSS at the time of its need, (b) SDSS are very high strength Materials, Fabrication is highly Time Consuming;**
- **Challenges on Materials Sourcing have already been discussed in the earlier slides. Now, the following slides will detail the fabrication challenges.**

Fabrication Challenges – SDSS are very high strength materials, Fabrication is highly time consuming:

- **Challenges during processing for preparation of Weld Fit-Up:**

- **Fabrication: Welded connection** – Major means of piping fabrication and assembly/erection process.
  - The extent of welded connections could vary widely depending on the size of the topside structure.
- **Quantity of Piping Works:** In a large-sized topside project of about 19 thousand metric tons of weight, there will be approximately
  - **70 Km length of welded connections**
  - **56 Km of piping** comprises of CRA materials
  - **85.5 thousand but-welded joints** with CRA materials, where, approximately **55.27% joints are SDSS materials**.
- **Sawing/Cutting/Shearing: H**igher forces are required to deform the SDSS materials, as well as, difficult to saw, shear, slit and punch.
- **Plasma cutting and laser cutting etc.** – Same as SS, but it needs some adjustment in the parameters to cater for low sulfur content and slightly higher thermal conductivity. All these add time to process.
- **Edge Preparation and Machining:** Every welded joint needs edge preparation. **The chip breaking during machining of SDSS does not take place spontaneously like other steels, as these steels contain the lowest possible sulfur.** The chips are highly strong, sticky and abrasive to tool surface. So, there is a high tool wear in machining of SDSS, and become an expensive preparation works for welding.

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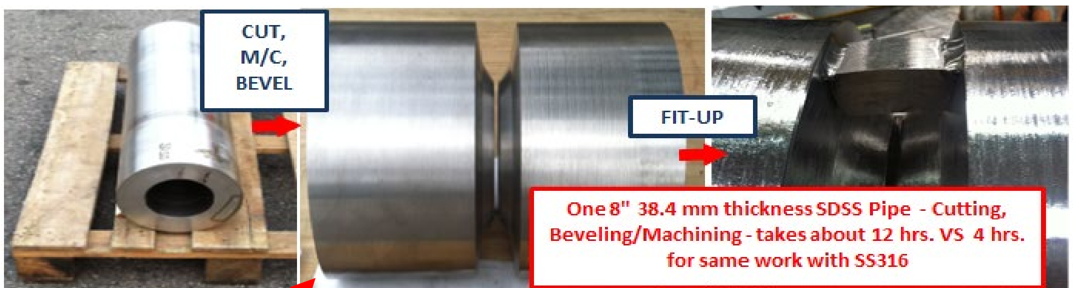
- **Fabrication Challenges – SDSS are very high strength materials, Fabrication is Highly Time Consuming:**
  - **Overview of SDSS Processing & Welding Challenges:**

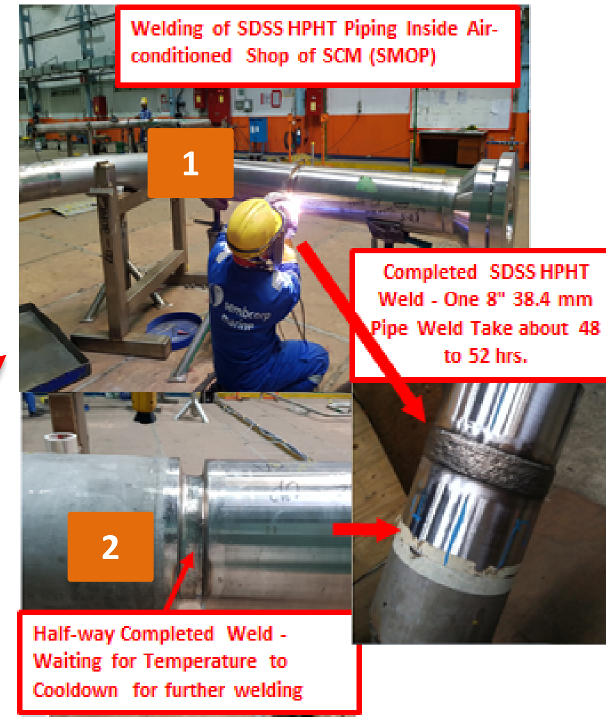
Processing for Weld Preparation



Edge Preparation - Cutting, Machining/Beveling: 8" Pipe, 38.4 mm thick		
SS – Require 5 to 6 hrs.	VS	SDSS – Require 12 to 14 hrs.

From Starting to Weld Completion: 8" Pipe, 38.4 mm thick		
SS – Require 8 to 10 hrs.	VS	SDSS – Require 48 to 52 hrs.

Completion of a SDSS Welded Joint



- **Highly Important Steps for SDSS:**
  - 1: Purge-out the air/oxygen to the desired ppm level from inside the entire volume of the pipe.
  - 2: Constantly monitor the process parameters, heat input and control them. Intermetallic phases like, Sigma, Nitrides, Alpha Prime can form within 1 or 2 minutes

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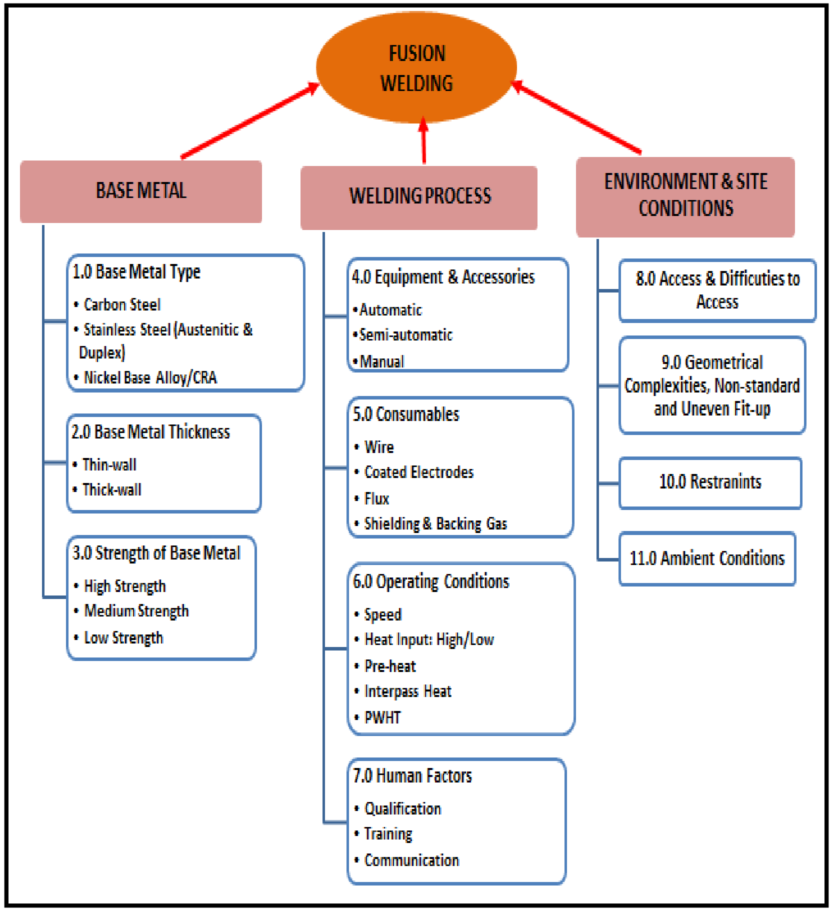
❑ Fabrication Challenges – SDSS are very high strength materials, Fabrication is Highly Time Consuming:

➢ Overview of SDSS Processing & Welding Challenges

- **Probability of Failure:** Materials, as well as, the welded connections in HPHT conditions (above 15,000 psi [1034 bar] and 350 F [177 C]) have a faster tendency to degradation, and so, these may be subjected to increased probability of failure.
- **Weld Performance:** Each Weld must remain leak free (no cracks or defects) throughout its service life, and must possesses adequate strength to sustain the intended load. Performance of each Weld is highly critical for safe operation of the platform.
- **Weld Histories:** Weld, with Sigma Phase, has histories of failure (crack).
- **Contributing Factors:** A number of contributing factors as shown in Fig need to consider to produce a defect-free workable welded joint.



Fabrication Challenges – SDSS are very high strength materials, Fabrication is Highly Time Consuming:

Defect-free Weld:

- **Strength:** Weld shall possess the same or higher strength than the base materials.
- **WPS:** This will be possible if the weld is done strictly through an established **Welding Procedure Specification (WPS)** and if it is confirmed that the weld is defect-free as tested nondestructively.
- **Tests:** Weld can be tested non-destructively to verify that it is defect free, but it (weld) can not be tested to verify its strength without destructions (destructive tests).
- Over the years, **many fabricators** around the globe have demonstrated capabilities to produce defect-free welds for common materials like carbon steels, austenitic (Type 304, 316 etc.) stainless steels (less probability of forming intermetallic compound).
- **SDSS Welded Joint:** But producing defect-free SDSS welded joints are challenging, as there is a high susceptibility of forming intermetallic phases, which impair toughness and corrosion resistance.
- **Intermetallic Phases:** Once intermetallic phase is formed, complete solution annealing followed by quenching are the only mitigation means to dissolve/remove the intermetallic phases. For welds or welded connections – the solution annealing is not practical. **Process selection, consumable selection and process controls are the means to overcome formation of intermetallic phases.**

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❑ Fabrication Challenges – SDSS are very high strength materials, Fabrication is Highly Time Consuming:

➢ Process Development – Research by Sembcorp Marine:

- **High strength thick-walled CRAs** like 25 Cr UNS No. S32750/S32760 Super Duplex with PREN of 40 to 45, is the major candidate material for HPHT process piping, riser piping or flowlines.
- **High Probability of Intermetallic Compound:** HPHT Materials like SDSS is highly alloyed materials, and very much susceptible to form intermetallic compounds, like Sigma Phase, Nitride etc.
- **Welding Process:** Welding Process that will yield high integrity and high production rate with such high strength (YS 550 MPa) **thick-wall SDSS (exotic material)** shall be employed.
- **Lowest Heat Tint:** Welding Process that will impart **'lowest possible heat input'** with 'lowest heat tint' shall be employed.
- **Conflicting Requirements:** The above requirements are conflicting to each other – generally, high production rate will be achieved with welding processes with high heat input. So, this requirement negates the second requirement of 'lowest possible heat input', and this is one of the most toughest challenges that the **Sembcorp Marine (SMOP) managed in the Fabrication of the HPHT Platform through innovative research.**

Process Control - before and during Welding

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❑ Fabrication Challenges – SDSS are very high strength materials, Fabrication is Highly Time Consuming:

➢ **Process Development – Research by Sembcorp Marine:**

- **High Integrity Weld Process:** Sembcorp Marine performed research by its in-house Research Team, and, employed the Weld Process with the appropriate Weld Parameters and Combination of Consumables that provided the Lowest Heat Tint, High Integrity, and Highest Passing rate (99.2% by Joint and 99.96% by length) for HPHT SDSS piping .
- **Manual and Semi-automatic:** It has used both Manual and Semi-automatic welding machines in a controlled environment

➢ **NDT-PAUT:** Phased Array Ultrasonic Test (PAUT) was employed for high thick HPHT Piping to optimize the requirements of Inspection Time. This was another research area that Sembcorp Marine has undertaken.

Semi-Automatic Welding for SDSS with continous monitoring of weld parameters & heat input

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❑ Overall Challenges:

- **In general, sourcing of materials for HPHT application is the biggest challenge among all. Specific requirements of multiple standards and codes set them on High Lead time.**
- **Additional Resource:**
  - Expediting: Sembcorp Marine stationed dedicated Procurement Manager and Expediting Team at Europe for entire duration of Bulk Material procurement phase.
  - Dedicated Team of Materials Engineer: Sembcorp Marine deployed a dedicated team of Materials Engineer to constantly support the Procurement Team with all technical information and reviews.
- **Resourcing of Noncomplying Materials:** Same challenges as with initial sourcing of materials, and it followed the same process of sourcing of new materials, as was done, for the first time.
- **Re-testing :** There was extremely limited time for re-testing of noncomplying materials, so at the end, it again translated to additional money to override the normal Q of the test program.
- **Shipment:** Whether heavy or light, huge or small, once the materials were ready for shipment, Airfreight was the only shipment mode to meet schedule. This was a huge cost-adding parameter to overall project cost.
- **Fabrication & Test/Inspection of the Corrective Works:**
  - Project Planning has no contingency for re-work or re-inspection, although, in the real world, we might not be able to find a Project (in oil and gas industry) without having rework (could be very minor, but still have). In most of the cases, the re-works were identified at the end stage of the project, virtually having no time.
  - To mitigate this conditions, EPC Contractor needs to engage additional work force to complete all the corrective works within the schedule.

Challenges In Resourcing And Fabrication Of High Thickness Super Duplex Stainless Steels – The Most Widely Used CRA For HPHT Services

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- **Specific Challenges with Super Duplex Stainless Steels (SDSS) – The Most Widely Used CRA For HPHT Services:**
- **Identified Areas: There could be a number of reasons for low impact values, for failure in tensile strength, having cracks and intermetallic phases, but the important points here to note are:**
    - All these non-complying/failed materials were having Type 3.1 Certifications, and the documented MTCs were showing impact values/tensile strength are well above the minimum requirement.
    - The materials were having acceptable test records for microstructural examination.
    - The certificates were pronouncing compliance with relevant codes, standards and regulations (like ASTM, NACE, PED, etc.).

But the actual condition is something different:

- These were non-complying materials, despite the availability of relevant complying records.
- Apparently, these non-complying materials snuck through all the quality gates of codes and standards, and finally become successful to stand in the same line of complying materials at the fabrication floor.
- Had there been no effective quality system in Sembcorp Marine or no random sampling test requirements, most of these noncomplying items would glide through the construction phase, would merge with the status of complying materials, and would have become the part of permanent works.

- **IMPROVEMENTS: From above example of challenges, it can be understood that there a number of cases, where improvements are required to make the regular certifications more effective.**

We Are Sembcorp Marine

Innovation & Engineering Company • Integrated Platform • Offshore, Marine & Energy

Sembcorp Marine Offshore Platforms

Integrated Breadth & Depth for Harsh Environment • Total Solutions • One-Stop EPC

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End of Presentation

THANK YOU