Influence of rapid cooling rates for HIP on mechanical and corrosion properties of UNS S32205

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- Duplex stainless steel UNS S32205
- Effects of cooling rate
- Influence of Process-Temperature
- Experimental
- Results
- Conclusion and discussion
Duplex stainless steel
UNS S32205
Duplex stainless steel UNS S32205

Composition in wt. pct.

- Carbon: 0.030 max
- Chromium: 22.0-23.0
- Nickel: 4.5-6.5
- Molybdenum: 3.0-3.5
- Nitrogen: 0.14-0.20
- Phosphorus: 0.035 max
- Manganese: 2.00 max
- Sulfur: 0.020 max
- Silicon: 1.00 max
- Iron: Balance

Source: J. Charles; Duplex Stainless Steels 1991
Duplex stainless steel UNS S32205

Properties

- Density: 7.80 g/cm³
- Specific heat: 460 J/Kg K
- Young's modulus: $19.5 \times 10^4$ MPa
- Melting range: 1420 – 1465 °C
- 0.2 % proof stress: > 450 MPa
- Tensile strength: 650 – 880 MPa
- Hardness: < 293 HB

Duplex stainless steel:
- Mixed microstructure
- Austenite / ferrite ratio usually 50/50 mix to 40/60
- Twice the strength compared to austenitic stainless steels
- Improved resistance to localized corrosion
- Lean duplex: PREN > 25
  - Standard duplex: ≈ 22% Cr
  - Super duplex: PREN > 40
  - Hyper duplex: PREN > 48

Duplex stainless steel is a type of stainless steel that has a mixed microstructure of austenite and ferrite, with an austenite / ferrite ratio usually between 50/50 and 40/60. It offers twice the strength compared to austenitic stainless steels and improved resistance to localized corrosion. Lean duplex stainless steels have a PREN value greater than 25, standard duplexes have a PREN value between 25 and 32, super duplexes have a PREN value greater than 40, and hyper duplexes have a PREN value greater than 48.
Duplex stainless steel UNS S32205

**Chromium equivalent**
\[ \text{Cr}_{eq} = \% \text{Cr} + 1.4\% \text{Mo} + \% \text{C} + 0.5\% \text{Nb} + 1.5\% \text{Si} + 2\% \text{Ti} \]
\[ \text{Cr}_{eq} = 27.65 \]

**Nickel equivalent**
\[ \text{Ni}_{eq} = \% \text{Ni} + \% \text{Co} + 0.5\% \text{Mn} + 0.3\% \text{Cu} + 30\% \text{N} + 30\% \text{C} \]
\[ \text{Ni}_{eq} = 9.76 \]
\[ \frac{\text{Cr}_{eq}}{\text{Ni}_{eq}} = 2.83 \]

Vertical section of an Fe-Cr-Ni phase diagram at 60% Fe
Norsok M-630 Standard / Duplex stainless steel UNS S32205

What is NORSOK?

Industry Initiative for the Competitive Standing of the Norwegian Offshore Sector

Norwegian Oil Industry Association

Federation of Norwegian Engineering Industries

Aims
- add value
- reduce cost
- lead time
- increase safety
- specify requirements

Standards

M630 – Material Data Sheets for Piping

M650 – Qualification of Manufacturers of „Special Materials“
- Duplex Stainless Steels
- High Alloyed Austentic Stainless Steels
- Nickel Base Alloys (Castings)
- Titanium and Alloys (Castings)
Norsok M-630 Standard / Duplex stainless steel UNS S32205

Requirements according Norsok M-630 Standard

Tensile Testing

\[ \begin{align*}
\text{R}_{p_{0.2}} & > 450 \text{ MPa} \\
\text{R}_{m} & > 620 \text{ MPa} \\
\text{A}_{5} & > 25 \%
\end{align*} \]

Hardness

maximum 28 HRC or 271 HB or 290 HV10

Impact Testing

according ASTM A 370 at \(-46^\circ\text{C}\)

minimum 45 J / single 35 J

Micrographic Examination

according ASTM E 562

35-55 % ferrite content
Effect of cooling rate
Effect of cooling rate

Time-Temperature-Transformation diagramm for various precipitates appearing in duplex stainless steel UNS S32205; source: M. Sorg; NACE-2015-5611

- $\sigma$-phase carbides
- $\chi$-phase
- $\text{Cr}_2\text{N}$
- $475^\circ\text{C}$-embrittlement
Effect of cooling rate

Approx. Cooling rate
1000°C-700°C: 1.7 K/min
over all: 0.2 K/min

χ-phase area
120-180 min

475°C – embrittlement
more than 10 h

TTT diagramm UNS S32205;
soure: M. Sorg; NACE-2015-5611

Approx. 46.0 % Austenite
32.5 % Ferrite
21.5 % intermetallic phases
Effect of cooling rate

Approx. Cooling rate
1000°C-700°C: 5 K/min
over all: 0.25 K/min

χ-phase area
30-60 min

475°C – embrittlement
more than 4 h

TTT diagramm UNS S32205;
soure: M. Sorg; NACE-2015-5611

Approx. 47.5 % Austenite
41.0 % Ferrite
11.5 % intermetallic phases
Effect of cooling rate

Approx. Cooling rate
1000°C-700°C: 10 K/min
over all: 0.35 K/min

χ-phase area
20-30 min

475°C – embrittlement
more than 4 h

Approx. 49.0 % Austenite
43.5 % Ferrite
7.5 % intermetallic phases
Effect of cooling rate

Approx. Cooling rate
1000°C-700°C: 20 K/min
over all: 0.5 K/min

χ-phase area
10-15 min

475°C – embrittlement
approx. 1h

Approx.
50.5 % Austenite
46.5 % Ferrite
3.0 % intermetallic phases

TTT diagramm UNS S32205;
soure: M. Sorg; NACE-2015-5611
Effect of cooling rate

Approx. Cooling rate
1000°C-700°C: 50 K/min
over all: 3.5 K/min

χ-phase area
5-10 min

475°C – embrittlement
10-20 min

Approx.
51.5 % Austenite
47.0 % Ferrite
1.5 % intermetallic phases
Effect of cooling rate

Approx. Cooling rate
1000°C-700°C: 60 K/min
over all: 15-20 K/min

χ-phase area
2-5 min

475°C – embrittlement
not reached

TTT diagramm UNS S32205;
sources: M. Sorg; NACE-2015-5611

Approx. 52.1 % Austenite
47.7 % Ferrite
0.2 % intermetallic phases
Effect of cooling rate

- increase the cooling rate
- reduce the process temperature

Temperature profile

TTT diagramm UNS S32205; source: M. Sorg; NACE-2015-5611
Influence of Process Temperature
**Influence of HIP-Temperature**

**Comparison of process temperatures**

- $1200^\circ$C
- $1140^\circ$C
- $1100^\circ$C
- $1040^\circ$C

**Without heat treatment**

**Approx. cooling rate**

- Critical temp.: 10 K/min
- Over all: 1 – 2 K/min

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Ferrite</th>
<th>Austenite</th>
<th>Intermetallic Phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1200^\circ$C</td>
<td>47%</td>
<td>47.5%</td>
<td>5.5%</td>
</tr>
<tr>
<td>$1140^\circ$C</td>
<td>47%</td>
<td>51.5%</td>
<td>1.5%</td>
</tr>
<tr>
<td>$1100^\circ$C</td>
<td>47.5%</td>
<td>50.5%</td>
<td>2%</td>
</tr>
<tr>
<td>$1040^\circ$C</td>
<td>47.5%</td>
<td>50%</td>
<td>2.5%</td>
</tr>
</tbody>
</table>
Influence of HIP-Temperature

Comparison of process temperatures

→ 1200°C
→ 1140°C
→ 1100°C
→ 1040°C

Without heat treatment

Approx. cooling rate

Critical temp.: 10 K/min
Over all: 1 – 2 K/min

Impact energy UNS S32205,
sources: M. Sorg; NACE-2015-5611
**Process Temperature**

**Resistance to crevice corrosion:**

Critical temperature for crevice formation in °C

- → 1200°C
- → 1140°C
- → 1100°C
- → 1040°C

**Comparison of process temperatures**

**Test medium**

6% FeCl₃ + 1% HCl

testing period 24h

**Corrosion Resistance according ASTM G48-03**
Experimental
**Experimental Setup**

**Goal**

evaluate benefits of fast cooling in industrial HIP facilities

**Process parameters**

**HIP-Temperature**

1140°C for 4 h

realized cooling rate

approx. 15-20°C/min

approx. 1,000 kg

**HIP-Samples**

- one-half conventional heat treatment
- one-half rapid cooling (HIP facility)
Investigated wall thickness / edge distance

- 10 mm / 5 mm
- 70 mm / 35 mm
- 120 mm / 60 mm
- 175 mm / 88 mm

Experimental Setup

Sample conditions:
- standard heat treatment with water quenching
- Jominy (ASTM A255-10 / DIN EN ISO 642) modified test setup
- no heat treatment after HIP
- HIP with rapid cooling (approx. 40 K/min)
Jominy End Quench Test ASTM A 255 is used to measure hardenability of steels

- hardenability is a measure of the capacity of a steel to be hardened in depth when quenched form its austenitizing temperature (usually 800°C to 900°C)
- specimen cylinder 100mm in length and 25mm in diameter
- cooling rate decreases form the quenched end to the air cooled end: different cooling rates are generated
- wall thickness cannot depict by the usual experimental setup

Goal

develop and prove a new and cost efficient test method to illustrate the influence of cooling parameters and wall thickness for HIP products
Jominy (ASTM A255-10 / DIN EN ISO 642) modified test setup

Modification

- increasing sample length from 100 mm to 200 mm
- add an isolation
- add several thermocouples
- drape in an aluminum casting
Results
Microstructure

Edge distance:
- 170 mm
- 65 mm
- 5 mm

Modified Jominy test setup

Standard heat treatment with water quenching

HIP-Process with rapid cooling
Austenite/Ferrite ratio

HIP with rapid cooling

HIP without heat treatment

edge distance in mm

volume in %

austenite  ferrite  precipitations
Corrosion resistance

Critical Pitting Temperature in °C according ASTM G150

- Standard heat treatment - water quenching
- modified Jominy test setup
- HIP-Process with rapid cooling
- HIP-Proces without heat treatment

thickness / edge distance in mm
Impact energy

brittle fracture

ductile fracture

The graph shows the notch impact energy according to ASTM A370, conducted at -46°C. The minimum requirement for impact energy according to NORSOK M-630 Standard is 45 J / single 35 J. Modified Jominy test setup and HIP-Process with rapid cooling and without heat treatment are indicated.

The diagram illustrates the edge distance in mm and the corresponding impact energy levels, showing the transition from ductile to brittle fracture.
Mechanical properties

**Hardness**

- max. 271 HB according to NORSOK M-630 Standard

**Yield strength**

- min. 450 MPa according to NORSOK M-630 Standard

**Corrosion**

- Standard heat treatment - water quenching
- HIP-Process with rapid cooling
Conclusion & Discussion
The results of corrosion measurements do not illustrate a significant effect of heat treatment or wall thickness / edge distance.

Demands and requirements of the NORSOK Standard will be achieved by fast cooling after HIP-Process only for thin-walled components (up to approx. 70mm).

A small amount of intermetallic phases shows no significant reduction of corrosion resistance.

Notch impact energy is affected very strong by a small amount of intermetallic phases / precipitations.

The fracture surface of non heat treatment specimens shows brittle characteristics due to precipitations.
High cooling rate / Quenching

**UNS S2205**

**Computational example:**

- **UNS S2205** 1.000 kg
- Specific heat capacity approx. 0.5 KJ/kg K
- Temperature difference 350 K (1000°C to 750°C)
- Specific heat 175 MJ
- To prevent intermetallic phases 120 seconds (175 K/min)
- Cooling power 1.45 MW
  - 1.45 kW/kg

TTT diagram UNS S32205;
source: M. Sorg; NACE-2015-5611
High cooling rate / Quenching

UNS No7718
INCONEL 718

... usually smaller components

... lower critical temperature difference to cross

... approx. 6 minutes to avoid intermetallic phases

TTT diagram IN718
source: A. Mostafa et. al; metals 2017 – 7, 196; 7060396
High cooling rate / Quenching

Computational example:

UNS No7718 INCONEL 718

- Specific heat capacity approx.: 0.435 KJ/kg K
- Temperature difference: 300 K (1050°C to 850°C)
- Specific heat: 130.5 MJ
- To prevent intermetallic phases: 360 seconds (50 K/min)
- Cooling power: 0.36 MW
- Cooling rate: 0.36 kW/kg

TTT diagram IN718
Source: A. Mostafa et. al.; Metals 2017 – 7, 196; 7060196
Process temperature is influencing
  - Ferrite/Austenite ratio
  - Grain size
  - Corrosion resistance

Rapid cooling rates
  - cannot replace conventional heat treatment to prevent intermetallic phases for thick-walled components made of UNS S32205
  - Help to accelerate the HIP-Process
    - Parts can removed faster from your HIP-unite
    - Increasing the economic efficiency of the HIP-process / HIP-facility
  - may be used for smaller parts or less sensitive materials
Thanks for your attention!