

**Design guideline to avoid hydrogen induced
stress cracking in subsea duplex stainless steels**

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Introduction

This guideline is based on the current industry practice and the experience gained by use of duplex stainless steels in sub-sea applications over the last 20 years and reflects the practice in several ongoing oil and gas projects including evaluation of known failure cases. The main body of the guideline covers the requirements, while best practice recommendations are provided as a supplement in the end.

Duplex stainless steels have shown susceptibility to HISC in subsea applications. Design, cathodic protection, material properties/microstructure, extent and type of coating and stress/strain level are factors influencing the risk for HISC. It is important to highlight that failures due to HISC have only occurred in very special cases, and have been due to over loading and sub-standard welds, see Annex D for an overview of known failures.

It is acknowledged that several research projects are ongoing and they may change the content of this guideline in the future.

The initiative for preparing this guideline was taken by the NORSOK material expert group K 114/EGM, *Materials*. With background in the severe failures cases there has been a need for a “quick fix” design guideline. A working group was established with representatives from the following companies:

- Aker Kvaerner Engineering & Technology
- Det Norske Veritas
- FMC Kongsberg Subsea
- Norsk Hydro
- Aker Kværner Subsea
- SINTEF
- Statoil
- Technip Offshore Norge
- Vetco Gray

The working group as such has been autonomous and the content of the guideline reflects the sum of experience and knowledge by the members within the group. Due to the need for a quick issuance the guideline is issued as NORSOK Workshop Agreement, for which the NORSOK procedure for industry hearing is not required. Further, it is anticipated that the guideline would have a limited lifetime until the matters for a safe design related to HISC for duplex materials have been documented by testing and implemented in recognized standards (e.g. ISO, API) and/or in a DNV Recommended Practice. Based on the mentioned reasons the guideline has been issued as a Workshop Agreement.

1 Scope

This guideline specifies design requirements in order to avoid HISC in duplex stainless steels in subsea applications when subjected to conventional cathodic protection, covering e.g.:

- manifold piping;
- pipelines, risers and associated components;
- umbilical end terminations.

2 Normative and informative references

The following standards include provisions and guidelines which, through reference in this text, constitute provisions and guidelines of this NORSOK standard. Latest issue of the references shall be used unless otherwise agreed. Other recognized standards may be used provided it can be shown that they meet or exceed the requirements and guidelines of the standards referenced below.

2.1 Normative references

DNV OS-F101, Submarine Pipeline Systems

2.2 Informative references

ASME VIII, Div.2, Appendix 4, Boiler and Pressure Vessel Code – Rules for Construction of pressure vessels

3 Terms, definitions, abbreviations and symbols

For the purposes of this NORSOK standard, the following terms, definitions and abbreviations apply.

3.1 Terms and definitions

3.1.1

can

verbal form used for statements of possibility and capability, whether material, physical or casual

3.1.2

duplex stainless steel (austenitic/ferritic stainless steel)

stainless steel whose microstructure at room temperature consists primarily of a mixture (50/50) of austenite and ferrite

3.1.3

hydrogen induced stress cracking

HISC

cracking that results from the presence of hydrogen in a metal and tensile stress (residual and/or applied)

3.1.4

may

verbal form used to indicate a course of action permissible within the limits of this NORSOK standard

3.1.5

shall

verbal form used to indicate requirements strictly to be followed in order to conform to this NORSOK standard and from which no deviation is permitted, unless accepted by all involved parties

3.1.6

should

verbal form used to indicate that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others, or that a certain course of action is preferred but not necessarily required

3.2 Abbreviations

API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
CP	cathodic protection
DNV	Det Norske Veritas
FEA	finite element analysis
HISC	hydrogen induced stress cracking
ISO	International Organization for Standardization
SCF	stress concentration factor
SMYS	specified minimum yield strength
SNCF	strain concentration factor
ULS	ultimate limit state

3.3 Symbols

σ	is the stress (indexes are according to criteria, see Clause 5)
ϵ	is the strain (indexes are according to criteria, see Clause 5)
Y_F	is the load effect factor (1,1 for ULS load condition (b), safety class normal), see DNV OS-F101, Table 5-6.
Y_C	is the condition load effect factor for functional loads according to DNV OS-F101, Table 5-7
E	is the Youngs modulus (= 200 000 MPa for duplex steels).

4 Technical requirements

The technical requirements in order to avoid HISC in duplex stainless steels can be summarized as follows:

- Keep control over interface loads and imposed loads during service life.
- Definition of stresses and strains shall be as specified in Clause 5.
- Design shall fulfil the requirements outlined in Clause 6.
- CP system shall be in accordance with the requirements given in Clause 7.

5 Design acceptance criteria - Stress and strain assessment

5.1 General

HISC is a non ductile mode of failure by an interaction between stresses, the CP system, and a susceptible duplex stainless steel material. Only loads acting while the structure is submerged, and the CP system is active, are therefore relevant. All load contributions causing stress and strain shall be included. The designer should be aware that deformation loads such as thermal stresses, subsidence effects, and residual stress which may be partly or completely disregarded in design for ductile modes of failure, shall be included, and that careful considerations shall be given to all effects contributing to peak tensile stress.

The design requirements herein are aimed at avoiding HISC. They are a supplement to, and not a replacement for, the selected design code. In case of conflict between the selected design code and the requirements in this document, the most stringent requirement shall apply.

5.2 Introduction to stress/strain assessment

The objective of the stress and strain criteria is to ensure that the loading does not initiate significant creep in the material. The following three separate criteria are established, each applying to different type of locations:

1. Stress/strain requirement for smooth pipe section without welds.
2. Stress/strain requirement for components.
3. Stress/strain for welds.

As a first assessment a linear elastic stress screening criteria according to 5.5, 5.6 and 5.7 could be performed. The analysis is based on global stresses and it is not taking into account SCFs and residual stresses. If the criterion is satisfied no further analysis is required.

If the linear elastic stress screening criterion is not satisfied the design may be checked against the global and the local non-linear strain criteria (where SNCFs and residual stresses are included), see 5.5, 5.6 and 5.7.

Design loads applicable to HISC are provided in Annex A, and procedure to determine SNCF values are given in Annex B.

5.3 Design parameters

5.3.1 Definitions of stresses and strains

Global strain refers to the strain distribution from a uniform cross section at a section beyond the zone of influence of any discontinuities. Local strain includes the contributions from all loads including residual stress, strain concentration and thermal strain.

Stress is in general defined as first principal stress (maximum acting tension stress).

Strain is in general defined as first principal strain (maximum acting tension strain).

When local stress distributions are determined by FEA local strain is the peak strain occurring at the external surface exposed to CP. The global strain may be determined as the peak value of the linear strain distribution due to the same cross sectional axial force and bending moment. This is illustrated in the figure below.

NOTE Linearization is dealt with in more detail in ASME VIII, division 2, Appendix 4.

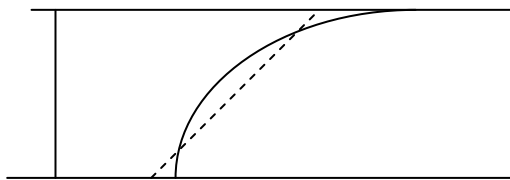
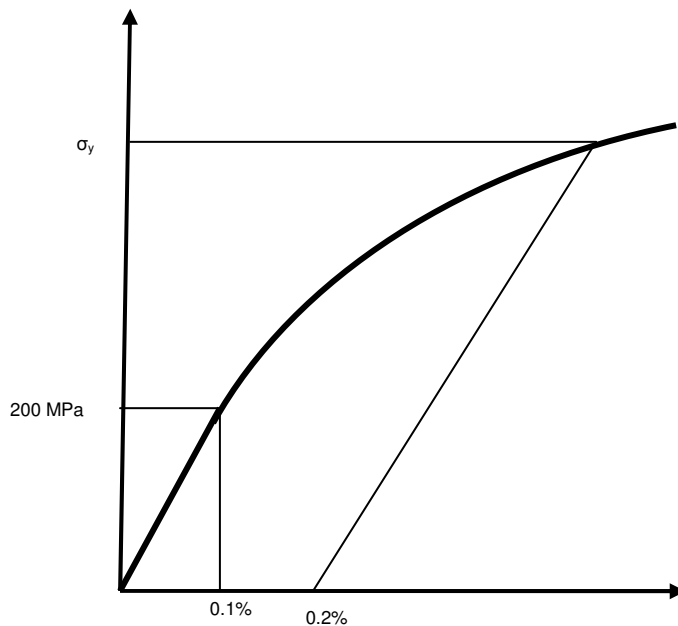


Figure showing the principle of linearization. The actual stress distribution through the wall thickness is represented by solid lines. The global stress distribution may be determined by linearization defining the stress distribution shown with a dashed line.

5.3.2 Effect non linear material properties

Materials such as duplex stainless steels have non linear stress-strain properties in the range of operational stress levels. This shall be taken into account where it has an impact on performance. If the material stress-strain curve is not determined from tests the curve shown below may be adopted. The curve shall be linear from zero to a point where 0,1 % strain corresponds to a stress of 200 MPa. From there on it shall be parabolic through a point corresponding to 0,2 % permanent strain and the specified 0,2 % proof stress.



The limits on stress and strain imposed for HISC design ensure that the effect of non-linearities will only be significant in localised areas. Structural analysis to determine load distribution and cross sectional forces may therefore be performed as conventional linear elastic pipe stress analysis using a Young's modulus of 200 000 MPa.

To determine the distribution of stress and strain across a cross section allowance shall be made for non-linearity.

5.3.3 Strain due to residual stress

Residual strain in welds shall be defined as 0,20 % unless otherwise justified.

5.3.4 Strain concentrations factors (SNCFs)

Global stress and strain levels across individual cross sections shall be determined taking account of material non-linearity. At welds, grooves and fillets, the global strain levels shall be amplified for stress concentration effects by applying a SNCF to which any strain due to residual stress shall be added to determine the total local strain.

Annex B gives guidance on SNCF.

5.3.5 Load factors

Safety margins such as load factors are not applicable for HISC. Material design factors are used, see 5.5, 5.6 and 5.7.

5.3.6 Bending and axial load

The proportion of global bending stress and stress due to axial load will influence creep. The current limitations on global stress provide conservative limits on creep strain.

5.3.7 Analysis

Local strain may be determined as the global strain found by non-linear analysis of the uniform pipe cross section multiplied by the appropriate SNCF. In addition, the residual strain may be added, if applicable (welds).

5.4 Non-linear strain – Acceptance criteria

When a non linear analysis is performed it is acknowledged that the threshold strain for initiating creep in the material is to be assessed both from globally and locally acting strains. Based on the data available from HISC testing, see /1/ and /2/, and the experience gained with sub-sea use of duplex materials for more than 20 years, the limit for global principal strain is 0,4 % for duplex stainless steels.

Provided the global principal strain is kept below 0,4 %, the local peak strain (total strain) due to SCNFs and residual strains, is allowed to be increased to 0,7 % for duplex stainless steels.

It is recognised that such local strain concentrations will be confined by material, which is strained below the global creep threshold strain. As a consequence there will be negligible increase in strain at these locations due to local creep, and thus the dominant effect would be stress relaxation.

5.5 Global strain requirement for pipe-sections (smooth sections without welds)

5.5.1 Screening criterion

$$\sigma_n \leq E \times \varepsilon_g = \sigma_g \quad (1)$$

where

σ_g is 0,80 x SMYS at specified design temperature
 ε_g is the strain corresponding to 0,80 x SMYS
 σ_n is the applied global stress (first principal)

NOTE No stress concentrations or residual stress need to be accounted for. Linear analysis can be applied.

5.5.2 Strain criterion

The global strain criterion is to ensure that the global stress level in a cross section does not exceed the level at which creep will contribute significantly to the total strain:

$$\varepsilon_n \leq \frac{\varepsilon_{g1}}{\gamma_F \times \gamma_C} \quad (2)$$

where

ε_{g1} is 0,4 % (g=global)
 ε_n is the non-linear applied membrane strain (first principal)

NOTE No strain concentrations or residual strains need to be accounted for.

γ_F is the load effect factor

The load effect factor is 1,1 for ULS load condition (b), safety class normal, see DNV OS-F101 Table 5-6

γ_C is the condition load effect factor for functional loads according to DNV OS-F101 Table 5-7

5.6 Local strain requirement for components

5.6.1 Screening criterion

$$\sigma_n \leq E \times \varepsilon_l = \sigma_l \quad (3)$$

where

σ_l is 0,80 x SMYS at specified design temperature
 ε_l is the strain corresponding to 0,80 x SMYS
 σ_n is the applied global stress (first principal)

NOTE Linear stress concentrations need to be accounted for. Linear analysis can be applied. Residual strains do not need to be accounted for.

5.6.2 Strain criterion

$$\varepsilon_n \leq \frac{\varepsilon_{lx}}{\gamma_F \times \gamma_C \times SNCF} \quad (4)$$

where

SNCF may be calculated directly in an FEA analysis (implicit in the strain value). Guidance on SNCF values is given in Annex B.

The criterion needs to be verified for the following:

1. $\varepsilon_{l1} = 0,4 \%$ (non-linear global – no SNCF and residuals, $l = \text{local}$), and
2. $\varepsilon_{l2} = 0,7 \%$ (non-linear local strains – peak strains, $l = \text{local}$)

ε_n is the maximum applied non-linear membrane strain (first principal)

NOTE If the applied strain is calculated by finite element analysis, the SNCF is automatically included and shall be ignored in the above formula.

γ_F is the load effect factor

The load effect factor is 1,1 for ULS load condition (b), safety class normal, see DNV OS-F101 Table 5-6.

γ_C is the condition load effect factor for functional loads according to DNV OS-F101 Table 5-7.

5.7 Local strain requirement for welds

5.7.1 Screening criterion

$$\sigma_n \leq E \times \varepsilon_w = \sigma_w \quad (5)$$

where

σ_n is the applied global stress (first principal)

NOTE Residual stresses and stress concentrations do not need to be accounted for. Linear analysis can be applied.

Butt welds with intact weld caps

σ_w is 0,60 x SMYS at specified design temperature

Ground butt welds

σ_w is 0,70 x SMYS at specified design temperature

Fillet welds

The screening criteria cannot be used and a detailed analysis shall be carried out.

5.7.2 Strain criterion

It is recognised that in the limited test data and field service failure data available relating to welds the effect of residual stress and stress concentration does not appear to be as critical as for local stress concentrations. Until further test data become available it is recommended to apply the same limits as for local stress concentrations.

$$\varepsilon_n \leq \frac{\varepsilon_{wx}}{\gamma_F \times \gamma_C \times SNCF} - \varepsilon_{residual} \quad (6)$$

where

SNCF may be calculated directly by FEA analysis (implicit in the strain value). Recommended values of SNCF are given in Annex B.

The criterion needs to be verified for the following:

1. $\epsilon_{w1} = 0,4 \%$ (non-linear global – no SNCF and residuals, w = welds), and
2. $\epsilon_{w2} = 0,7 \%$ (non-linear local strains – peak strains, w = welds)

$\epsilon_{\text{residual}}$ is 0,20 %

ϵ_n is the maximum applied non-linear membrane strain (first principal)

NOTE If the applied strain is calculated by finite element analysis, the SNCF is automatically included and shall be ignored in the above formula.

γ_F is the load effect factor

The load effect factor is 1,1 for ULS load condition (b), safety class normal, see DNV OS-F101 Table 5-6.

γ_C is the condition load effect factor for functional loads according to DNV OS-F101 Table 5-7.

6 Design requirements

6.1 Forged-to-shape

Forgings shall be forged as closely as practicable to the specified shape and size. The forging process shall result in a grain flow that follows the shape of the forging to the largest possible extent, in order to reduce the risk for HISC.

Flanges, elbows, return bends, tees and header tees shall not be machined directly from bar stock.

6.2 Design requirements for grooves and fillets on components

The radius in transition fillets shall not be less than one third of the wall thickness.

6.3 Design requirements for welds

If welds are closer to local stress concentrations (e.g. local transition fillets) than $2,5\sqrt{rt}$, weld residual stress shall be allowed for.

7 Cathodic protection requirements

Subsea structures (e.g. manifolds) will consist of both structural elements and piping that normally are made of different materials that are electrically connected, and the sacrificial anodes are often attached to the structural elements. This practice should be maintained to limit the number of welded connections to the duplex piping.

Initiation of HISC by CP can only take place if the electrochemical potential is more negative than -850 mV (Ag/AgCl). Duplex stainless steels are well protected for potentials more negative than -600 mV (Ag/AgCl), hence a polarisation to -600 mV can in principle be applied for these materials. However, this requires a complete electrical isolation from the structural elements, which are protected at -1050 mV. A reduced polarisation is thus only a practical method to eliminate HISC for pipelines that can be isolated from other structures that require more negative potentials.

Annex A (Informative) Design loads applicable to HISC

Definition of loads applicable to HISC

As a minimum the following load cases have to be evaluated:

- tie-in;
- sub sea pressure test;
- operation;
- shut-down;
- thermal effects.

Temporary loads such as dropped object and other sudden loadings do not apply. On the other hand, temporary loading such as pressure testing, maximum tie-in loads shall be investigated.

The load factors to be used in the analyses are 1,0 for all external loads (i.e. forces and moments from installation and operational loads) and 1,0 for internal pressure.

Annex B **(informative)** **Methodology to define stress concentration factors**

Elastic pipe stress analysis that does not include the effects of stress concentrations will produce global or nominal stresses. At welds, grooves or fillets, the global stresses shall be corrected for stress concentrations or stresses or strains can be calculated directly by use of a proper material model and non-linear FEA.

A typical linear analysis will only be representative until about 0,1 % (linear range) for super duplex and duplex materials. Due to the fact that stress and strain factors are non-linear above a certain level, a simplified approach is established to provide guidance to the designer, as follows:

1. For ground welds: SCF = 1,2
2. For non-ground butt welds: SCF = 1,2 x 1,6 = 1,96
3. For fillet welds: SCF is a function of radius and wall thickness, and shall be calculated by use of formulas or by FEA.
4. For more optimized SCFs, see equations (B.1) and (B.2).
5. Detailed analysis needs to be performed for fillet welds.

The stress-strain properties of austenitic-ferritic steels are in general significantly non-linear. The limitations on stress levels imposed by the provisions for HISC limit stress to a level where linear elastic pipe stress analysis will determine sectional forces with sufficient accuracy. To determine cross sectional strain distribution these non-linear properties shall, however, be properly taken into account. This requires non-linear FEA of the cross section. Non-linearity does on the other hand have little impact on SNCFs and strain due to residual stress.

Local strain can therefore be determined reliably by multiplying the strain determined in a non-linear analysis of the uniform section and multiplying it with the appropriate SNCF the discontinuity detail being considered and adding the strain due to the residual stress at this location.

SNCF values may be determined sufficiently accurately by two dimensional or axisymmetric FEA.

The following values of strain concentrations may be applied if more accurate assessments are not made. Mismatch at girth welds cause a strain concentration given by the following expression:

$$SNCF = (1 + \delta/t) e^{\frac{1}{3} \sqrt{t/D}} \quad (B.1)$$

The mismatch is the result of the aggregate effect of diameter tolerance, tolerance on alignment and tolerance on ovalisation.

NOTE As piping will be aligned for the external surface wall thickness tolerance will not impact on the SNCF for the external HISC exposed surface.

The aggregate effect of these may be estimated as the root-mean square of half the tolerance on the diameter, half the tolerance on ovality and the tolerance on alignment. If a more detailed investigation is not performed, a geometric SNCF of 1,2 may be assumed for shop welded girth welds. This geometric SNCF is applicable for welds which have been ground flush such that there are absolutely no ridges causing stress concentration and the surface is completely smooth.

For welds with intact weld caps there will be additional strain concentration due to the weld notch effect which can be taken as equal to 1,6.

The total SNCF for a weld with an intact weld cap is obtained by multiplying the geometric SNCF with the SNCF due to the weld notch.

For transition fillets the following values may be adopted:

$$SNCF = \frac{4}{10r/t - 0,8} \quad (B.2)$$

Annex C

(informative)

Best practice

C.1 Coating recommendations

Initiation of HISC by CP of commonly applied ferritic-austenitic (duplex) stainless steel grades requires that the metal surface is electrochemically polarised to a potential more negative than -850 mV (Ag/AgCl). Hydrogen atoms will be produced on the metal surface and some of this hydrogen will enter the metal lattice, which is one prerequisite for HISC. An intact surface coating will act as a barrier between the metal surface and the water and will prevent hydrogen production and reduce risk for HISC from CP.

In the past, polymeric coatings have primarily been applied to reduce the current demand from the sacrificial anodes and are then normally not expected to act as a 100 % safe barrier. Even rather tight crevices associated with dis-bonded coating can lead to significant local hydrogen production, and if this coincides with a location with significant stresses, HISC can occur.

The type of coating that normally is applied subsea depends on the type and size of the component and the environmental conditions (primarily the operating temperature). For pipelines, the weakest point in a coating is normally in the field joints and where the factory coating is penetrated. In many cases this coincides with locations where the highest operational stresses can be found.

A coating shall therefore not be used as the only mean to prevent HISC by CP. The combined material selection and design with respect to maximum allowable stress/strain shall be made such that HISC shall not occur even if the coating is destroyed or removed. On the other hand, many of the reported HISC failures are in fact caused by upset loading conditions beyond the design value. Whenever practical, components in duplex stainless steels that may become exposed to high stresses during installation or in service should be coated with a coating system qualified for resistance to dis-bonding at the applicable operating temperature.

Coating materials and application procedures must be adequately qualified for resistance to dis-bondment by mechanical and physical/chemical effects. Metallic coatings applied by welding can be considered immune to dis-bonding and the use of metallic materials with very low hydrogen permeability to prevent HISC of a susceptible base material should be considered for special applications.

C.2 Material recommendations

It has been demonstrated that a smallest possible austenite spacing reduce the risk for HISC for duplex stainless materials. Except for heavy forgings an austenite spacing $\leq 30 \mu\text{m}$ should be aimed for. For heavy forgings an austenite spacing of $60 \mu\text{m}$ should be aimed for. Components should be forged-to-shape (or as close as possible) or manufactured by hydrostatic pressing (HIP).

Annex D **(informative)** **Background data for design criteria**

Duplex and super duplex stainless steels have been extensively used in sub-sea applications the past 20 years. More than a hundred sub-sea structures having duplex and super duplex materials in the piping systems have been installed. To the knowledge of the Working Group (see Introduction) there are reported eight HISC failure cases (six sub-sea installations), which are listed in the table below. It is noted that these failures mainly are related to tie-in components and tie-in spools, and they can be summarised as follows:

- High loads giving unacceptable high strains exceeding the critical stress/strain threshold for initiating and propagation of HISC cracks in duplex materials are reported to be the reason for the failures in four of the eight referenced cases.
- Fillet socket welds containing substandard ferrite content, i.e. > 80 % is reported to be reason for HISC failures in three of the eight cases. In one case high strain due to sub-sized throat thickness was reported to be the reason.
- For five of the eight cases no coating was applied, for the remaining three cases the coating was damaged.
- Both 22Cr duplex and 25Cr Duplex have suffered from HISC.

Project	Product	Grade	Quality characteristics	Coating	Stress/Strain in failure area	Remarks	Ref.
Foinaven	- 2 off forged manifold tie-in hub (6"x6"x2")	25% Cr UNS S32760	- Coarse grained structure (approximately 120 µm) - Grain orientation in through thickness direction - Unfavourable design (short nibs) causing high SCFs	No		- Cracking in nib area in base material - Leakage during pressure testing	/1/
Garn West	- 1 off forged 12 in inboard tie-in hub	25% Cr UNS S32760	- Coarse grained structure	No		- Cracking both in base material and weld Note: The HISC investigation on Garn West is still not finished and the final conclusion has not been drawn.	/6/
Britannia	- 1 off fillet weld on carbon steel sleeve - 5 in tie-in spool	22% Cr	- Fillet weld questionable, could have contained pre-existing cracks	Damaged	Strain > 3,5 %	- High strain due to seabed subsidence and rock dumping	/6/
	- 2 off in "Opened up" flange - 5 in tie-in spool	22% Cr	- "Good quality"				/6/
Scott	- 1 off fillet weld on doubler plate - 6 in tie-in spool	22% Cr UNS 31803	- 29 ppm hydrogen close to surface	Damaged	Strain 2 % to 3 %	- High strain caused thermal expansion and steady displacement of spool along seabed	/6/
Balder	- 7 off fillet socket welds on umbilical termination, hydraulic piping	22% Cr UNS 31803	- Ferrite content about 80 % - Large blocks of ferrite grains running in continuous network through weld	No		- High strain due to sub-sized throat thickness of 2 mm (3,5 mm required from calculations) - Leakage during pressure test	/6/
	- Fillet welds in pressure transducers	Duplex stainless steel	- Ferrite content 94 % to 97 % - Heavy nitride precipitations	No			/6/
West Africa project	- 5 off fillet socket welds connectors gas lift system wall thickness 19 mm and 36 mm	22% Cr pipe, 25% Cr body	- Ferrite content > 80 %	No		- Fillet weld throat thickness down to 2 mm	/6/

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