RECOMMENDED PRACTICE
DNV-RP-F112

DESIGN OF
DUPLEX STAINLESS STEEL
SUBSEA EQUIPMENT EXPOSED TO
CATHODIC PROTECTION

OCTOBER 2008

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FOREWORD

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**Amendments and Corrections**

This document is valid until superseded by a new revision. Minor amendments and corrections will be published in a separate document normally updated twice per year (April and October).

For a complete listing of the changes, see the “Amendments and Corrections” document located at: http://webshop.dnv.com/global/, under category “Offshore Codes”.

The electronic web-versions of the DNV Offshore Codes will be regularly updated to include these amendments and corrections.
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SECTION 1
GENERAL

A. General

A 100 Introduction

101 Both 22Cr and 25Cr duplex (ferritic-austenitic) stainless steels have been extensively used for subsea equipment. These types of steels have been used as rolled/extruded pipes, small bore tubing, hubs, fittings and valve bodies manufactured by castings, forgings or HIP. In general the experience is good but some significant failures have occurred.

The main reason for these failures has been attributed to an unfortunate combination of load/stress and local hydrogen embrittlement (HE) caused by ingress of hydrogen formed at the steel surface due to the cathodic protection. In this document this is referred to as Hydrogen Induced Stress Cracking (HISC).

Guidance note:
Other terms used include e.g. hydrogen embrittlement stress cracking, hydrogen induced cracking and hydrogen cracking. However, none of these terms, or HISC, is specific to the source of the hydrogen.

Other materials commonly used in the offshore industry may also be prone to HISC when exposed to cathodic protection. However, only duplex stainless steels are addressed in this Recommended Practice.

Testing of typical small scale laboratory specimens has shown that the duplex stainless steels are susceptible to HISC when exposed to elevated stresses in conjunction with cathodic protection potentials more negative than about -850 mV relative to the Ag/AgCl/seawater reference electrode. Furthermore, there are indications that materials with coarse austenite spacing are more susceptible to HISC than those with fine austenite spacing. Full scale tests have given failures at reduced stress/strain levels compared to simple laboratory tests. This is believed to be due to residual stresses/strains from welding and fabrication.

The aim of this Recommended Practice is to provide a best practice based on today’s knowledge, experience from in-service failures and recent research. This is driven by the following factors:

— a need for operators and contractors to have a harmonized approach to the design of duplex stainless steel components exposed to CP
— a need for increased awareness of hydrogen embrittlement due to CP within the industry.

A 200 Scope

201 This Recommended Practice covers all components made from duplex stainless steels that are installed subsea and are exposed to cathodic protection.

A 300 Objective

301 The objectives of this document are:

— to give detailed recommendations on loads and conditions that need to be considered in the design of subsea systems where duplex stainless steels will be used in conjunction with cathodic protection
— to define other parameters affecting the resistance to HISC, such as CP potential, surface characteristics (i.e. coating), temperature and specific configurations requiring particular attention
— to give stress/strain design criteria
— manufacturing, fabrication and test recommendations are only given when they are believed to have a direct impact on the material’s resistance to HISC.

302 This RP does not address how loads are to be estimated, how load factors are to be applied and how the risk related to uncertainty in loads is assessed.

A 400 Relation to design codes

401 This Recommended Practice is applicable in conjunction with any recognized design code (e.g. ASME B31.3, ASME B31.4, ASME B31.8, ASME VIII, DNV-OS-F101, ISO 13623, EN 14161, API 6A, API 17D, ISO 10423, PD 8010).

In case of conflict between requirements of this Recommended Practice and a referenced design code, the most stringent requirement shall apply.

B. References

The latest revisions of the following documents apply.

B 100 DNV Offshore Standards

DNV-OS-F101 Submarine pipeline systems

B 200 DNV Recommended Practices

DNV-RP-C203 Fatigue strength analysis of offshore steel structures
DNV-RP-B401 Cathodic protection design
DNV-RP-F102 Pipeline field joint coating & field repair of line pipe external coating
DNV-RP-F103 Cathodic protection of submarine pipelines by galvanic anodes
DNV-RP-F106 Factory applied external pipeline coatings for corrosion control

B 300 Certification notes and Classification notes

DNV CN 7 Non Destructive Testing

B 400 Other references

ASME VIII Boiler and Pressure Vessel Code
ASME B31.3 Process Piping
ASME B31.4 Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids
ASME B31.8 Gas Transmission and Distribution Piping Systems
ASTM E112 Standard test method for determining average grain size
NORSOK M-001 Material Selection
NORSOK M-601 Welding and inspection of piping
NORSOK M-630 Material data sheets for piping
NORSOK M-650 Qualification of manufacturers of special materials
ISO 13623 Petroleum and natural gas industries – Pipeline Transportation Systems
EN 14161 Petroleum and natural gas industries – Pipeline Transportation Systems
ISO 10423 / API 6A Drilling and production equipment – Wellhead and Christmas tree equipment
API 17D
PD 8010 Published Document 8010
Guidance note:
The latest revision of the DNV documents may be found in the publication list at the DNV website www.dnv.com.

C. Definitions

C 100 Verbal forms

101 “Shall”: Indicates requirements strictly to be followed in order to conform to this Recommended Practice and from which no deviation is permitted.

102 “Should”: Indicates 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. Other possibilities may be applied subject to agreement.

103 “Recommend”: Indicates the preferred method. Other suitable alternatives may be permitted subject to agreement.

104 “May”: Verbal form used to indicate a course of action permissible within the limits of the Recommended Practice.

105 “Agreement”, “by agreement”: Unless otherwise indicated, this means agreed in writing between Manufacturer/Contractor and Purchaser.

C 200 Terminology

201 Cathodic protection potential: Potential of the steel surface relative to the Ag/AgCl/seawater reference electrode.

202 Design temperature, maximum: The highest possible temperature to which the equipment or system may be exposed during installation and operation. Environmental as well as operational temperatures shall be considered.

203 Design temperature, minimum: The lowest possible temperature to which the equipment or system may be exposed during installation and operation, irrespective of the pressure. Environmental as well as operational temperatures shall be considered.

204 Duplex stainless steel (DSS): Stainless steels containing both a ferrite and an austenite phase.


206 Hydrogen Induced Stress Cracking (HISC): Cracking due to a combination of load and hydrogen embrittlement (HE) caused by ingress of hydrogen formed at the steel surface due to the cathodic polarisation.

207 Load: Any action causing stress, strain, deformation, displacement, motion, etc. to the equipment or system.

208 Load effect: Effect of a single load or combination of loads on the equipment or system, such as stress, strain, deformation, displacement, motion, etc.

209 Pressure, Design: This is the maximum internal pressure during normal operation, referred to at a specified reference height, to which the system shall be designed. The design pressure must take account of steady flow conditions over the full range of flow rates, as well as possible packing and shutting conditions, over the whole length of the pipeline or pipeline section which is to have a constant design pressure.

210 Residual stress: Stress in the material induced by the manufacturing process, welding or previous permanent deformation for which applied loads have been relaxed. There are no applied loads associated with residual stress.

211 Residual strain: Strain associated with residual stress.

212 Resistance: The capacity of a structure or part of a structure, to resist load effects.

213 Specified Minimum Tensile Strength (SMTS): The minimum tensile strength prescribed by the specification or standard under which the material is purchased.

214 Specified Minimum Yield Stress (SMYS): The minimum yield stress prescribed by the specification or standard under which the material is purchased.

215 Strain: Strain is defined as relative deformation associated with applied loads or residual stresses. Non-linear strain is established using a non-linear stress strain curve. For HISC evaluation only strain incurred when the component is subject to cathodic protection shall be taken into account.

216 Stress: Stresses should, in general, be established based on the applied loads. If specifically stated residual stresses should be included. Linear stress refers to stresses calculated assuming a linear elastic behaviour.

217 Submerged zone: The part of the system or installation below the splash zone, including buried parts.

218 System pressure test: Final test of the complete system.

D. Abbreviations and Symbols

D 100 Abbreviation

API American Petroleum Institute
ASME American Society of Mechanical Engineers
ASTM American Society for Testing and Materials
CP Cathodic Protection
CTOD Crack Tip Opening Displacement
DNV Det Norske Veritas
DSS Duplex Stainless Steel
FE Finite Element
FEA Finite Element Analysis
HAZ Heat Affected Zone
HE Hydrogen Embrittlement
HIP Hot Isostatic Pressing
HISC Hydrogen Induced Stress Cracking
NDT Non-Destructive Testing
PWHT Post Weld Heat Treatment
PT Penetrant Testing
RP Recommended Practice
RT Radiographic Testing
SCF Stress Concentration Factor
SENB Single Edge Notch Bend
SENT Single Edge Notch Tensile
SIF Stress Intensity Factor
SMTS Specified Minimum Tensile Strength
SMYS Specified Minimum Yield Stress
UT Ultrasonic Testing
WT Wall thickness

D 200 Symbols

ε = Residual strain
σ = Residual stress
r = Distance from weld for which residual strains have to be taken into account in design
\( i_\alpha \) = Average austenite spacing for field
S = Nominal stress, excluding SCF
\( \sigma \) = Local stress, including SCF
\( \varepsilon \) = Local strain, including SCF
K = Elastic strain concentrator
\( H_{\text{HISC}} \) = Material quality factor
\( \sigma_{\text{HISC}} \) = Allowable stress factor, membrane stress
\( \sigma_{\text{HISC}}^{\text{mb}} \) = Allowable stress factor, membrane plus bending stress
\( \sigma_{\text{mb}} \) = Membrane stress
\( \sigma_{\text{b}} \) = Bending stress
R = Nominal pipe radius
t = Wall thickness
SECTION 2
DESIGN PHILOSOPHY

A. General
A 100 Objective
101 The objective of this Recommended Practice is to outline the primary concerns related to HISC in the design of subsea equipment made from duplex stainless steels.

A 200 General considerations
201 This Recommended Practice presents requirements based on the resistance to HISC of duplex stainless steel grades. The choice of characteristic loads, load factors and target safety level is not described in this document. This shall either come from the project design code or be based on company requirements.

202 It is important to plan for NDT as early as possible in the design phase. The design of components should make welds accessible for the required NDT. See also Section 6 A100.

B. Safety Philosophy
B 100 Safety objective
101 An overall philosophy for avoiding HISC shall be established, planned and implemented, covering all phases from conceptual development until abandonment of the system.

Guidance note:
HISC is an area with insufficient data to quantify failure probability as a function of parameters such as stress, strain, CP potential etc. The intention is however that the design limitations set forward in this document ensure low failure probabilities.

The main criteria are for stress and strain in the material. The values presented in this Recommended Practice are based on laboratory testing, and reflect the material’s resistance. This document does not give requirements concerning the loads, except for listing the type of loads that shall be taken into account. The choice of characteristic loads and load factors is not specified in this Recommended Practice, and shall be based on the project design code or company requirements.

The requirements in this Recommended Practice are assumed to be conservative, and it is the opinion of DNV that the probability of HISC failure is negligible when stress and strain are below the limits set forth. The probability of HISC failure for stress and strain above the limits is not known.

Determination of the safety level is done from an evaluation of the statistical distribution of material resistance together with the statistical distribution of the loads. At present there is not enough data for a statistical distribution of the resistance to HISC. This Recommended Practice does not go into the statistical distribution of the loads, this must come either from the governing design code or other project documents.

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B 200 Systematic review
201 A systematic review or analysis shall be carried out in all phases in order to identify and evaluate the consequences of single failures and series of failures in the subsea system, such that necessary remedial measures can be taken. The extent of the review or analysis shall reflect the criticality of the subsea system, the criticality of a planned operation, and previous experience with similar systems or operations.

Special attention shall be given to sections close to installations or shore approaches where there is frequent human activity and thus a greater consequence of failure.
SECTION 3
LOADS AND CONDITIONS

A. General

A 100 Objective

This section gives recommendations regarding the assessment that should be carried out when duplex stainless steel is to be exposed to cathodic protection.

A 200 Aspects to be considered

201 A major part of the assessment is to consider stresses and strains. Detailed acceptance criteria for this are given in section 4.

202 Section 3 gives guidance regarding the loads that have to be considered when stresses and strains are established.

203 In addition to loads and stresses the following aspects should also be considered during design of a system:

---certain design details require particular attention or should be avoided (fillet welds, sharp edges, stress raisers)---
---coating is a significant risk-reducing measure---
---adjustment to a less negative level may also reduce the risk for HISC.

204 Unintentional overloading has previously caused failures by HISC, in particular due to external loads. It is important that a thorough evaluation is made of the type of loads that can act on a structure or component, as well as the loads’ magnitude and uncertainty. This RP does not address how loads are to be estimated, how load factors are to be applied and how the risk related to uncertainty in loads is assessed.

B. Design

B 100 Applicable design codes

101 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 RP, the most stringent requirements shall apply.

C. Loads

C 100 General

101 HISC is a non ductile mode of failure caused by an interaction between stresses, the cathodic protection system and a susceptible material. All stresses acting while the structure is submerged and the CP system active are therefore relevant. All load contributions causing stress and strain shall be included. The designer shall be aware that deformation loads, such as thermal stresses, seabed subsidence effects and residual stress, which may be partly or completely disregarded in design for ductile modes of failure, must be included when designing for HISC resistance. For cases with a large number of combined loads it is recommended to carry out an assessment based on finite element analysis (FEA).

102 For HISC to occur, a load has to be applied over a certain time interval. In laboratory tests, however, HISC failures have been produced in a matter of hours. Hence, all loads except momentary loads shall be considered.

C 200 External loads

201 If the code or standard used for design of a component does not take into account forces other than the internal pressure, then additional calculations shall be carried out in order to address the maximum forces that can be transferred to the component from the connecting system during installation and operation.

202 When establishing design loads for subsea systems there may be relatively high uncertainties. This is due to uncertainties in input parameters such as soil interaction, pipeline behaviour, installation and rock dumping. An assessment of the uncertainty on the established loads shall be made, and this shall be related to the target safety level of the project design code or company requirements.

203 It shall be ensured that correct interface/tie-in loads between different parts of the subsea system are communicated. It shall also be ensured that all parties involved have a common understanding of the uncertainties related to the communicated loads.

C 300 Pressure containment

301 The design criteria for stress/strain given in this RP shall be fulfilled for all pressures to which the system will be exposed while in a submerged position and CP system is active. This also includes subsea pressure testing.

C 400 Incidental loads

401 A brief shock load (dropped objects, fishing gear/trawl impact, ships, anchoring, earthquake etc) will not lead to failure by HISC.

402 The duration of any incidental load shall be evaluated. If the load will act on the structure or component for longer than a couple of minutes the strains and stresses shall be evaluated against the limits in this RP.

403 Brief incidental loads can induce deformation and build residual stresses and strains into the structure and components. These permanent, residual strains and stresses shall not exceed the limits given in this RP.

Guidance note:
This Recommended Practice does not set any requirements to protection against incidental loads, nor the acceptable level of damage from such loads. Such requirements shall be defined by the project, the project design code or company requirements.

Incidental loads, such as trawl impact, dropped object and earthquake, will typically have a short duration, and the loads from such events can be neglected from a HISC point of view. Key words are shock load, short duration of a couple of minutes and impact.

Incidental loads can introduce deformation in the structure, or change the soil conditions or support. A new assessment of external loads may be necessary after an accidental load.

---end of Guidance note---

C 500 Installation loads

501 As long as the parts and components considered are submerged and cathodic protection is active no loads during installation shall lead to higher stresses/strains than given in this Recommended Practice.

502 For installation loads that are applied for only a very short time higher stresses/strains may be accepted, see also C400 Incidental loads.

503 For installation pressure test, see C300 Pressure containment.

504 Reeling may introduce residual stresses in the material. This shall be evaluated, see also Section 4 C400.
C 600 Lifetime assessment

601 The design shall cover the full design life of the subsea system.

602 Relative settlement (seabed subsidence) between different parts of the subsea system shall be properly assessed, since this can introduce additional stresses and strain in the material.

C 700 Residual stresses

701 Residual stresses shall be taken into consideration. Residual stresses associated with welds are addressed in Section 4. Welds should not be located close to areas with stress concentrations. See also Section 4 C 400 for residual stress related to welds.

C 800 Temperature

801 The susceptibility for HISC is believed to decrease when temperatures increase.

802 At elevated temperatures there is no change in the design criteria in this RP. A cut off temperature above which HISC does not need to be considered has not yet been established.

Guidance note:
Further work is being conducted concerning the effect of temperature on HISC.

---end-of-Guidance-note---

D. Design details

D 100 Sharp cracks

101 This RP assumes that no sharp cracks are present in the material. If it is considered likely that sharp cracks exist, a detailed assessment is recommended. In particular surface breaking cracks are critical with regards to HISC.

Guidance note:
Fracture toughness testing of pre-cracked duplex stainless steel specimens exposed to CP consistently show CTOD values below 0.05 mm. This indicates a significant increase in the susceptibility to HISC in the presence of sharp cracks. Engineering Critical Assessments indicate that only very small surface breaking cracks can be tolerated. This should be taken into account for the NDT.

---end-of-Guidance-note---

D 200 Fillet welds

201 Fillet welds shall not be used as pressure retaining welds in systems carrying hydrocarbons.

Guidance note:
Fillet welds used for attachment of doubler plates, pipe supports etc are not pressure retaining.

---end-of-Guidance-note---

202 Fillet welds shall not be used unless satisfactory weld geometry and microstructure can be documented. Fillet welds are in many cases more susceptible to high ferrite contents than butt welds due to low heat input and quicker cooling.

Guidance note:
Several of the known duplex stainless steel HISC failures are related to fillet welds. If fillet welds are used they shall be given high attention, with regards to weld material quality, coating quality and load levels.

Satisfactory weld geometry and microstructure can be documented by performing WPQ testing or production testing on samples with a similar geometry.

---end-of-Guidance-note---

E. Coating

E 100 General

101 Polymeric coatings have primarily been applied to reduce the current demand from the sacrificial anodes and/or for thermal insulation. They are then normally not expected to act as a 100% effective barrier. Even quite narrow crevices associated with disbonded or damaged coating can lead to significant local hydrogen production and absorption. If this coincides with a location with high stresses, HISC can occur. The type of coating that normally is applied on subsea components depends on the type and size of the component and the internal fluid and environmental conditions (primarily the operating temperature).

102 Coating shall normally not be used as the only means of preventing HISC by CP. The combined materials selection and design with respect to maximum allowable stress/strain shall ideally be such that HISC will not occur even if the coating is damaged or removed.

Guidance note:
The use of high integrity coatings may justify higher utilisation of duplex stainless steel materials than allowed by this RP. Any use of coatings for this purpose will require a comprehensive review of all relevant factors related to coating materials, coating application procedures and degradation mechanisms that could affect the capability of the coating to ensure a reliable barrier to hydrogen ingress. This is not included in this RP.

---end-of-Guidance-note---

Guidance note:
Some of the reported HISC failures were caused by upset loading conditions beyond the design value. Whenever practical, components in duplex stainless steel that may become exposed to high stresses during commissioning or in service (i.e. with CP applied) should therefore be coated with a coating system qualified for resistance to disbonding at the applicable operating temperature. Coating materials and application procedures shall be adequately qualified for resistance to damage and disbonding by mechanical and physical/chemical effects. The design life and possible coating degradation should be taken into consideration.

For pipelines the weakest point in a coating system is normally in the field joints and where the factory coating has been deliberately penetrated (e.g. for fastening of anodes). In many cases this coincides with locations where high operational stresses occur.

---end-of-Guidance-note---
SECTION 4
DESIGN CRITERIA

A. General

A 100 Objective

101 This section provides design and acceptance criteria for duplex stainless steels exposed to CP.

Guidance note:
Generic components (such as instruments and sensors) made from DSS shall also meet the requirements in this RP. However, the DSS in such components are typically of standard design, and can be verified on a type approval basis, not on a project specific basis. This requires that limitations on loads and other conditions (see Section 3) are clearly stated.

102 The design criteria in sub-section D and E are equally applicable. A design meets the requirements of this RP if it satisfies the criteria in one of the sections. A design does not need to meet the criteria of all the sections.

Guidance note:
In most cases the criteria in sub-section D are stricter than the criteria in sub-section E. However, there may be cases where sub-section E give stricter requirements than sub-section D.

A 200 Limitations

201 The allowable stresses and strains presented in this section presuppose that the material complies with the requirements and recommendations in section 5 of this RP, and that the loads and conditions have been assessed according to section 3.

202 Particular attention should be given to components with unfavourable microstructure. For materials with excessive austenite spacing and grain flow perpendicular to the main loading direction the stress and strain levels required in this document may be non-conservative.

203 HISC shall be taken into consideration when a surface can be exposed to CP and when hydrogen can diffuse into the region in question. If it can be conclusively shown that neither CP nor hydrogen can influence a volume or surface in the component the limits in this RP do not need to be taken into account.

204 A pure compressive stress and strain state do not need to be evaluated against the HISC criteria. Only tension may lead to HISC. However, when calculating equivalent stress all directions shall be included, even if in one direction the stress is compressive.

B. Characteristic material properties

B 100 General

101 The different material grades refer to mechanical properties at room temperature. Possible temperature effects shall be considered for temperatures above room temperature.

102 The design criteria in this Recommended Practice shall apply for temperature de-rated SMYS and stress-strain curve. The temperature derating shall be based on one of the following (in prioritised order):

— project design code derating requirements
— testing of the material to be used; testing according to design code requirements
— derating requirements from another applicable design code

Guidance note:
Most design codes present some way of derating metallic materials. Note that DNV-OS-F101 presents a derating curve for duplex stainless steel from 0°C to 200°C that can be used.

103 If the de-rating is based on testing of the material to be used, such data shall either be obtained from the material supplier, or based on project-specific testing.

104 A threshold temperature above which HISC does not need to be considered has not yet been established.

105 The design limits in this RP are valid only in the absence of sharp cracks in the material. In particular surface breaking cracks are critical.

C. Load and Resistance Calculations

C 100 Design

101 The design format in this RP supposes compliance with a selected design code. In case of conflict between requirements in the selected design code and this Recommended Practice, the more stringent shall apply.

C 200 Load effect calculation

201 All loads and forced displacements which may influence the integrity of the subsea system shall be taken into account. For each cross section or part of the system to be considered, all relevant combinations of loads which may act simultaneously shall be taken into account.

C 300 Influence of austenite spacing

301 A significant difference has been found in the resistance to HISC between fine and coarse austenite spacing, see Section 5. This Recommended Practice presents different acceptance criteria for materials with fine and coarse austenite spacing.

C 400 Assessment of residual stress and strain

401 Residual stress and strain, \( \sigma_{\text{res}} \) and \( \varepsilon_{\text{res}} \), from any operation or load must be taken into account when assessing a structure. In particular welding, installation and reeling operations can induce residual stresses in the structure, and these shall be evaluated.

402 Girth welds can contribute to residual stress effects that can lead to cold creep of duplex materials affecting the HISC resistance. This effect is more prominent close to the girth weld, and shall be taken into account in the assessments.

403 Attachment welds and small fillet welds that do not impart significant residual stresses on the component/pipe cross-section do not affect the creep potential of nearby duplex material. However, these details can include stress raisers, which shall be taken into account in both the stress and strain based assessments.

404 In the region near girth welds \( \sigma_{\text{res}} \) and \( \varepsilon_{\text{res}} \) shall always be taken into account. The region in which \( \sigma_{\text{res}} \) and \( \varepsilon_{\text{res}} \) need to be considered near a weld is defined as a distance \( L_{\text{res}} \) on each side of the weld. Beyond \( L_{\text{res}} \) the residual stresses and strains may be considered negligible. A design specific assessment should be made to establish \( L_{\text{res}} \) and \( \varepsilon_{\text{res}} \).
405 Residual stress and strain from welds that are parallel to the stress direction under consideration do not need to be taken into account. This means that residual stresses at a girth weld do not need to be considered for the hoop direction, while a longitudinal weld does not need to be considered for the axial direction.

406 After a complete heat treatment of a component residual stresses and strain from welding are considered negligible and do not need to be taken into account for the HISC design criteria.

Guidance note:
For pipe girth welds the following may be used as an estimate of $L_{\text{res}}$:

$$L_{\text{res}} = 2.5 \sqrt{R_t}$$

where

- $R = \text{nominal pipe radius}$
- $t = \text{wall thickness}$

The distance $L_{\text{res}}$ shall be taken from the weld centreline. The values in Table C1 may be used as an estimate of residual strain for girth welds in the absence of measurements of the actual residual strain.

Table C1 Estimates of residual longitudinal strains for girth welds

<table>
<thead>
<tr>
<th>Location</th>
<th>$L_{\text{res}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>At weld toe</td>
<td>0.15%</td>
</tr>
<tr>
<td>From HAZ to $L_{\text{res}}$ (all the weld except the weld toe)</td>
<td>0.25%</td>
</tr>
</tbody>
</table>

If an FEA, which include an initial residual strain distribution, shows a beneficial effect of pressure testing, the demonstrated effect can be used to reduce the values found in Table C1. However, the acceptable strain within $L_{\text{res}}$ shall under no circumstance exceed that outside $L_{\text{res}}$.

--- Guidance note ---

D 100 General

101 Residual stresses related to welds, see C400, are accounted for in the stress limits, and do not need to be taken into account further in the linear stress analysis.

102 Misalignment at weld connection shall be accounted for in the analysis. It is not required to include weld geometry.

Guidance note:
The misalignment shall be taken into account due to the bending stress it induces. Note that this includes misalignment at welded connections between all types of components, not only pipe and tubing.

The misalignment can alternatively be included as an SCF at the weld. This is commonly done in fatigue analysis, and DNV-RP-C203 presents methods for calculating such SCFs.

If nothing else is specified, it is recommended to use the difference between the mean/nominal and maximum/minimum tolerance. It is typically not necessary to use the difference between maximum and minimum tolerance.

--- Guidance note ---

D 200 Stress analysis methods

201 The component shall be modelled and stress calculated according to the requirements in the project design code.

--- Linear elastic FEA with sufficient refinement through-thickness to capture relevant bending stress component can be used ---

Piping stress analyses can be used where the structure is primarily composed of piping. The through-thickness stresses can be extracted from the pipe stress output.

202 For HISC evaluation, the stress shall be linearised over the wall thickness in the principal directions. The stress shall be linearised into two elements; membrane stress and bending stress. The peak stress can be disregarded in HISC assessments.

The membrane stress is a uniform stress that is in force equilibrium with the actual stress distribution. The bending stress is a linear bending stress that is in moment equilibrium with the actual stress distribution (through-thickness). The peak stress is the maximum stress of the actual stress distribution. This is illustrated in Figure 1.

More information concerning linearised stress can be found in the 2007 edition of ASME VIII, Division 2, Part 5, section 5.2.2.3.

--- Guidance note ---

Guidance note:
For piping stress analyses, the local membrane stress is the through-thickness average of the longitudinal stresses that include global cross-sectional bending. SCFs can be used to account for localised through-wall bending. The membrane plus bending stress is then the product of the local membrane stress and the SCF.

The maximum axial stress reported in piping stress analyses can be used as a conservative approximation of the membrane stress for HISC assessment. Appropriate SCFs can be used with membrane stress to compute local bending stresses for HISC assessment.

--- Guidance note ---

D. Linear elastic stress criteria

203 The following four items shall be evaluated against the acceptance criteria in D300, Equations 4-1 and 4-2:

1. membrane stress, $\sigma_{m}$:
   - a) membrane stress in the principal directions
   - b) equivalent membrane stress calculated from the membrane stress components in the principal directions.

2. membrane plus bending stress, $\sigma_{m+b}$:
   - a) membrane plus bending stress in the principal directions
   - b) equivalent membrane plus bending stress calculated from the membrane plus bending stress components in the principal directions.
Note: For cases when the absolute value of the maximum principal stress is smaller than the absolute value of the minimum principal stress it is justified to disregard the equivalent stress and only consider the maximum principal stress when evaluating the susceptibility to HISC. This may, for example, be applicable for cases with internal pressure in combination with axial compression.

D 300 Stress limits

301 The limits are expressed as percent of SMYS. The SMYS value shall be temperature adjusted, see B100. The stress limits are:

\[
\sigma_m < \alpha_m \cdot \gamma_{HISC} \cdot \text{SMYS} \quad (4.1)
\]

\[
\sigma_{m+b} < \alpha_{m+b} \cdot \gamma_{HISC} \cdot \text{SMYS} \quad (4.2)
\]

Both limits shall be met. The coefficients \( \alpha_m \) and \( \alpha_{m+b} \) are the allowable stress factors from Table D1, and \( \gamma_{HISC} \) is a material quality factor from Table D2.

302 A design where the stress everywhere in the component is below 80% of \( \gamma_{HISC} \cdot \text{SMYS} \) is acceptable. The peak stress can be disregarded.

303 The membrane stress check shall be met everywhere (Equation 4.1).

304 The membrane plus bending check shall be met everywhere (Equation 4.2). The total bending plus membrane stress has different limits depending on the severity of the local detail (see Figure 2):

- Outside of \( L_{res} \) from a girth weld centre-line the bending plus membrane stress is limited to 100% of \( \gamma_{HISC} \cdot \text{SMYS} \) for smooth details without weld toes or stress risers.
- Within \( L_{res} \) of a girth weld centre-line the bending plus membrane stress is limited to 90% of \( \gamma_{HISC} \cdot \text{SMYS} \) for smooth details without weld toes or stress risers.
- Outside of \( L_{res} \) from a girth weld centre-line the bending plus membrane stress is limited to 90% of \( \gamma_{HISC} \cdot \text{SMYS} \) at weld toes and stress risers (see C403).
- Within \( L_{res} \) of a girth weld centre-line the bending plus membrane stress is limited to 80% of \( \gamma_{HISC} \cdot \text{SMYS} \) at weld toes and stress risers.

305 A microstructure with fine austenite spacing has higher stress limit than coarse austenite spacing as shown in Table D2. The material shall be considered to have coarse austenite spacing unless otherwise established, see C300.

306 If the stress is above this limit one of the following apply:

1) a more detailed assessment of the component can be made.
2) the non-linear strain criteria may be invoked
3) the component may have to be redesigned to lower the stresses.

307 Stress components parallel to a weld can be considered outside of \( L_{res} \). See also C405. This does not apply to the equivalent stress.

### Table D1 Allowable SMYS factor for duplex stainless steel

<table>
<thead>
<tr>
<th>( \alpha )</th>
<th>Area considered</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>80% Membrane stress (( \sigma_m ))</td>
<td>Everywhere</td>
<td>D303</td>
</tr>
<tr>
<td>100% Membrane plus bending stress (( \sigma_{m+b} ))</td>
<td>Smooth sections without stress raiser or welds - outside of ( L_{res} )</td>
<td>D304</td>
</tr>
<tr>
<td>90%</td>
<td>Smooth sections within ( L_{res} )</td>
<td></td>
</tr>
<tr>
<td>90%</td>
<td>Weld toes attachments (see C403) and stress raisers - outside of ( L_{res} )</td>
<td></td>
</tr>
<tr>
<td>80%</td>
<td>Weld toes and stress raisers - within ( L_{res} )</td>
<td></td>
</tr>
</tbody>
</table>

Note: The value for SMYS at elevated temperatures shall be adjusted for temperature effects, see B100.

### Table D2 HISC material quality factor

<table>
<thead>
<tr>
<th>Material</th>
<th>( \gamma_{HISC} )</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine austenite spacing</td>
<td>100%</td>
<td>D305</td>
</tr>
<tr>
<td>Coarse austenite spacing</td>
<td>85%</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2

Illustration of the membrane plus bending stress criteria listed in Table D1

(A design check of the membrane stress only shall also be carried out)
E. Non-linear strain criteria

E 100 General

101 The design may also be checked against non-linear strain criteria. The objective of the strain assessment is to ensure that the loading does not initiate significant cold creep and HISC in the material.

E 200 Finite element analysis

201 A non-linear finite element analysis (FEA) using a non-linear material hardening description shall be performed. Creep strain should not be included in the non-linear strain evaluation.

202 Misalignment, geometric transitions and welds shall be included in the calculations.

203 The material hardening curve to be used shall have the following characteristics:

— SMYS and the strain hardening curve shall be corrected for relevant high temperature conditions, see B100.

The material hardening curve to be used may have the following characteristics:

— linear elastic to 0.1% total strain
— 80% of SMYS corresponds to 0.3% total strain
— SMYS corresponds to 0.5% total strain.
— an appropriate curve should describe the strain hardening after 0.5% strain

Guidance note:

Stress/strain data measured by tensile tests on samples taken from the component may be used in the FEA if enough tests have been made to enable a statistical assessment of property variations.

204 The FE model shall have sufficient mesh refinement through-thickness to capture relevant strain gradients.

E 300 Neuber’s rule

301 When the linear stress criteria are not met, an approach with Neuber’s rule may be used as a first approximation around strain and stress concentrations in a component. The results shall be evaluated based on the criteria in Table E1.

302 Neuber’s rule can be written as follows:

\[ K_t^2 \cdot S \cdot e = \sigma \cdot \varepsilon \]

with

\( S \) and \( e \) = nominal stress and strain (excluding SCF)
\( \sigma \) and \( \varepsilon \) = local stress and strain (including SCF)
\( K_t \) = elastic strain concentrator

E 400 Allowable strain

401 Allowable initial maximum principal strain is found in Table E1.

Table E1 Allowable initial maximum principal strain from all loads
(This is the sum of elastic and plastic strain, excluding creep strain)

<table>
<thead>
<tr>
<th>Location in the component</th>
<th>Strain criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Within ( L_{res} ) from weld</td>
<td>Minimum of [0.30% ; 0.50% - ( \varepsilon_{res} )]</td>
</tr>
<tr>
<td>Outside ( L_{res} ) from weld</td>
<td>Fine austenite spacing</td>
</tr>
<tr>
<td>Within 5% WT from surface</td>
<td>Coarse austenite spacing</td>
</tr>
</tbody>
</table>

Notes:

— For austenite spacing and \( L_{res} \), see C300 and C400.
— Thermal expansion/contraction may be neglected. Mechanical strains due to temperature loads, on the other hands, shall be included.

Guidance note:

Thermal expansion/contraction of components leads to strain in the material. However, this strain is not necessarily a risk factor for HISC. If the component is free to expand/contract, stresses will not be induced in the material. On the other hand a component that is mechanically/physically restricted will experience mechanical stresses due to thermal strains.
SECTION 5
MATERIAL REQUIREMENTS

A. General

A 100 Objective

101 This section gives some specific requirements for materials. This includes the following:

— limitations and general requirements related to materials that shall be met in order for the design criteria in this Recommended Practice to be applicable
— requirements that shall be met in order to obtain what is considered to be sound duplex stainless steel material
— guidance related to improving the resistance of the duplex stainless steels to HISC.

B. Material limitations

B 100 General

101 This Recommended Practice covers material generally referred to as 22Cr and 25Cr duplex stainless steel (DSS). The limitations set on materials for which the design criteria in this Recommended Practice apply are primarily based on limits in available test data. It is recommended that if materials outside the limits given below are to be used a detailed assessment should be carried out and qualification testing considered.

B 200 Chemical composition

201 Typical UNS numbers for 22Cr duplex stainless steels are S31803 and S32205.

Typical UNS numbers for 25Cr duplex stainless steels are S32550, S32750 and S32760.

B 300 Mechanical properties

301 The field experience with duplex stainless steels is primarily from applications where the SMYS given in the material standards has been applied in design. Taking benefit from higher actual mechanical test data in design is therefore not recommended. The recommendations given in this RP are therefore only applicable if the SMYS at room temperature is not higher than 450MPa for 22Cr duplex stainless steel and 550MPa for 25Cr super duplex stainless steel.

302 SMYS for material in the weld area shall be taken equal to the SMYS of the base material.

B 400 Heat treatment

401 The materials should be supplied as solution annealed and water quenched.

B 500 Austenite spacing

501 HISC cracks generally propagate in straight cleavage through the ferrite phase. The crack may be arrested or propagate through the austenite phase depending on crack size and stress level. Consequently, all fabrication techniques that tend to decrease austenite spacing (free ferrite path) are favourable. Testing confirms that materials with a fine phase spacing have a greater resistance to HISC than materials with a coarse phase spacing.

502 The following materials are assumed to have a microstructure with fine austenite spacing:
— HIP materials.
— Weld metal. However, the HAZ has the same austenite spacing as the base material.
— Tube and pipe made by extrusion, seamless rolling or drawing. All dimensions and wall thicknesses are included. This also includes fittings made from such pipes and tubes.
— Rolled plate with wall thickness less than 25 mm. This also includes pipes and fittings made from rolled plate with such wall thickness.

503 Materials that do not fall within the categories presented in 502 shall be considered to have coarse austenite spacing, unless physical measurements of the austenite spacing indicate otherwise.

Guidance note:
Test and failures have shown that adverse grain flow – when the ferrite grains are oriented perpendicular to the principal stresses – can give increased susceptibility to HISC. For items with an anisotropic grain structure (forged or rolled material) the manufacturing route should be reviewed to ensure a favourable grain flow.

---end-of-Guidance-note---

504 Materials that do not fall into the categories in 502 can be tested by measuring the austenite spacing. The austenite spacing is considered fine if it is less than 30 micrometers. Section 7 describes one acceptable method for measuring the austenite spacing. If such testing is carried out the extent and frequency of testing, as well as detailed measuring procedures and acceptance criteria, are subject to agreement.

Guidance note:
The limit of 30 micrometers is not a strict limit, since the uncertainty of austenite spacing results often are of the same order as the results themselves. However, the number is included in this Recommended Practice as a guidance value.

---end-of-Guidance-note---

C. General Requirements

C 100 General

101 A number of standards and company specifications exist for materials, welding, testing and manufacturers and it is not within the scope of this Recommended Practice to cover all aspects related to these issues. Recommended tests to ensure proper material properties include:
— metallographic characterisation of the microstructure (ferrite content, inter-metallic phase precipitation, austenite spacing)
— corrosion test according to ASTM G48
— impact tests at an appropriate temperature.

102 Acceptable requirements for duplex stainless steels, welding, testing and documentation are specified in DNV-OS-F101. The requirements in NORSOK M-601 and M-630 are also considered acceptable.

C 200 Qualification testing

201 A standard test with clearly defined acceptance criteria to test the susceptibility to HISC of materials exposed to cathodic protection has not yet been established. Qualification testing has to be agreed.

---end-of-Guidance-note---
**Guidance note:**

If a project finds it relevant to carry out qualification testing it is recommended that the test program is set up based on a project specific assessment. It is however most relevant to use tests which have been performed previously on similar materials in order to be able to compare the results from testing to reference data.

Possible tests of duplex stainless steels exposed to CP include:
- hanging load tests on smooth specimens
- fracture mechanics CTOD test with fatigue cracks (SENB, SENT)
- testing similar to SENB or SENT specimens with notches simulating real stress raisers
- segment testing to assess the effect of stress concentrations or weld toes
- full scale or semi-full scale segment testing.

---end---of---Guidance---note---
SECTION 6
NON DESTRUCTIVE TESTING

A. General

A 100 General

101 There are some specific NDT issues related to duplex stainless steels and HISC. Fracture mechanics testing of duplex stainless steels exposed to CP has given CTOD values consistently below 0.05 mm. It has therefore been concluded that there is a high vulnerability to defects in general, and surface breaking defects in particular.

102 X-ray and UT both have their weaknesses and strengths. As a general rule the best result is achieved if testing is done using both techniques. There is, however, not enough available data to state exactly how much the probability of detection of defects is increased if both techniques are used compared to just one.

103 The design of all components should make welds accessible for the specified NDT.

104 It is recommended that critical components are given a shape during manufacturing or are machined to an intermediate stage where the geometry allows as high volumetric NDT coverage as possible.

B. Extent of NDT

B 100 General

101 The extent of NDT shall be according to agreement and as a minimum in compliance with applicable standards, which are specified by the project or company.

102 The extent of NDT should reflect the criticality of the object to be inspected.

Guidance note:
Criticality is primarily decided by applied loads and the level of stress and strain in the material. It is recommended to consider more extensive NDT in the following instances:

- when there are large uncertainties related to applied loads
- for new designs and new components, for which there is limited manufacturing experience
- in critical applications, as defined by the project.

---end---of---Guidance---note---

C. Methods and Procedures

C 100 General

101 When performed, NDT methods should take into consideration the recommendations in this RP and the relevant NDT specification such as DNV-OS-F101 revision 2007, EN 10228 or equivalent.

Guidance note:
Experience with NDT on duplex stainless steels have shown that the characteristics of the material may make testing more difficult than for carbon steel.
UT of duplex materials is more complex than for carbon steel. Specific procedures and operator training are necessary, and all calibration must be carried out on representative duplex material. PT procedures should have a penetration time of at least 60 minutes before developing.

---end---of---Guidance---note---

D. Visual Inspection

D 100 General

101 For design according to this Recommended Practice there will in general be a large emphasis on correct design of details such as fillets, transitions and welds. It is therefore crucial that during construction an inspection regime is put in place to check that the as-built structures are according to applicable design drawings.
SECTION 7
PROCEDURE FOR ASSESSMENT OF AUSTENITE SPACING

A. General

A 100  Objective

101 This section proposes a procedure for assessing the austenite spacing in the microstructure of duplex stainless steel.

B. Specimen sampling

B 100  Base material

101 It is important that the austenite spacing is measured in a plane representing the likely cracking direction, i.e. in directions perpendicular to the stresses acting on the material. It can generally be assumed, if nothing else is stated, that this plane is in the through thickness direction.

102 The metallographic sample on which the measurements are made can in general be oriented parallel to the longitudinal axis. It should however be considered whether measurements on a surface perpendicular to the longitudinal axis are relevant (Typically if hoop stresses are dominant).

103 For relatively thin-walled components, the specimens should cover the entire wall thickness. For components with substantial wall thickness, the test specimens should at least cover the sub-surface region (close to outer surface) and also the mid thickness region. Note that if the components are to be machined, the shape after machining shall be considered when specimen locations are decided.

104 For components with variable wall thickness (i.e. forgings, castings) the austenite spacing shall be measured in sections with a wall thickness which is comparable to the maximum wall thickness of the forging prior to machining. The position of the austenite spacing measurements in the through thickness direction shall be related to the dimension of the component after final machining. Measurements are recommended at the external surface after machining and at the centre. Analysis shall not be carried out closer than 1/3 WT to the edge of the forging after heat treatment.

C. Microstructure assessment

C 100  General

101 Prior to conducting austenite spacing measurements a general assessment of the microstructure in the sample that is being examined should be carried out. The presence of any deleterious phases or particles (e.g. sigma phase, carbides, nitrides) should be reported. All reported findings should be documented with micrographs.

102 The following should also be reported:

— whether the austenite appears to be homogeneously distributed in the samples
— whether equiaxed austenite phases present in “clusters” between considerably larger austenite islands are observed.

Such phases may be ignored during austenite spacing measurements

— whether individual large ferrite units are observed.

D. Measuring the austenite spacing

D 100  General

101 It is recommended to specify that austenite spacing measurements are carried out according to ASTM E112-96 with amendments indicated in this document. This is a reference known in most laboratories. It will ensure that general issues such as equipment calibration and reporting are carried out according to generally recognized industry practice. Requirements relevant for measurement of austenite spacing are given in paragraph 17 of ASTM E112-96.

D 200  Line intercept measurement with individual measurements

201 It is recommended that the measurements are done according to the line intercept method with measurement of each ferrite element. This procedure is described in ASTM E112-96 paragraph 17.6 and paragraph 13.

202 The austenite spacing is typically measured by superimposing 4-5 parallel lines over a microscope or printed image of the microstructure of interest. Along these, the length of the line falling in each ferrite unit is measured. The total number of measurements should be greater than 50. The magnification used for the measurements shall be chosen so that typically 10 to 15 micro-structural units are intersected by each line, and could vary between 50X and 1000X.

203 Measurements should be carried out in four different random fields in the area of interest (i.e. on each test specimen and location to be examined). The austenite spacing to be reported is the average of all the measured values in all four fields. In addition, the standard deviation obtained from all measurements should be reported. Fine equiaxed austenite phases present in “clusters” between considerably larger austenite islands may be ignored (see Figure 2).

204 For fine microstructures usually observed in weld metal and thin walled tubes, the austenite spacing will normally be carried out at high magnification. The surface area examined will, therefore, be very small. In this case more emphasis should be put on the general assessment of the microstructure (Section 5).

D 300  Statistical analysis

301 ASTM E112-96 paragraph 15 describes how the accuracy of the measurements should be assessed. This is done by calculating the average austenite spacing for each of the four fields. The standard deviation “s” obtained using these four values is then calculated. This standard deviation is then used to calculate the 95% confidence interval “95% CI” and the relative accuracy “%RA”, “s”, “95% CI” and “%RA” are to be reported. According to ASTM E-112-96 the procedure may need to be revised if “%RA” exceeds 10%.
E. Figures

Figure 1
Typical micrograph with lines used to measure austenite spacing

Figure 2
Micrograph showing fine austenite phases present in “clusters” between considerably larger austenite islands