



RECOMMENDED PRACTICE
DNV-RP-F112

DESIGN OF DUPLEX STAINLESS
STEEL SUBSEA EQUIPMENT
EXPOSED TO
CATHODIC PROTECTION

DRAFT ISSUE APRIL 2006

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DET NORSKE VERITAS

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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This document is valid until superseded by a new revision.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://www.dnv.com/technologyservices/>, "Offshore Rules & Standards", "Viewing Area".

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1. General

1.1 General

1.1.1 Introduction

Both 22Cr and 25Cr duplex stainless steels have been extensively used for subsea equipment. These types of steels have been used as pipes, castings, forgings and small bore tubing. 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 hydrogen embrittlement (HE) caused by ingress of hydrogen formed at the steel surface due to the cathodic protection. This is called Hydrogen Induced Stress Cracking (HISC).

Laboratory testing of simple specimens have shown that the duplex stainless steels are susceptible to HISC when exposed to elevated stresses in conjunction with Cathodic Protection potentials lower than typically -850 mV relative to the Ag/AgCl/seawater reference electrode. There are furthermore indications that coarse grained materials are more susceptible to HISC than fine grained materials. 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.

There is a need within the industry for a guideline reflecting a best practice based on today's knowledge. 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 this issue within the industry.

The design criteria may be perceived as conservative compared to what has been applied successfully in the past. It is important to emphasize that this conservatism is partly due to the limited amount of test data available.

Further work is required to be able to base design recommendations on a sound amount of test data and a fundamental understanding of the involved mechanisms. Current work is attempting to close these technology gaps. It is the intent that this guideline will be updated to implement the results of this work.

1.1.2 Scope

The objectives of this Design Guideline are:

- To be an Industry Design Guideline that will define the best practice for design and fabrication of duplex stainless steels for subsea equipment exposed to Cathodic Protection.
- The document gives detailed recommendations on characteristic load effects that need to be considered in the design of subsea systems where duplex stainless steels will be used in conjunction with cathodic protection (Section 3).
- Other parameters affecting the resistance to HISC such as cathodic protection level, surface characteristics (i.e. coating) temperature and specific configurations requiring particular attention are covered (Section 3).
- The document gives stress/strain design criteria (Section 4). When the requirements set on linear stresses are not fulfilled, a more refined non-linear finite element analysis has to be carried out. Stress/strain criteria as well as procedures for how these refined finite elements assessments should be done are given.
- General manufacturing, fabrication and test recommendations intended to ensure a sound duplex stainless steel are

given (Section 5). This is, however, done as briefly as possible. The main focus of this document is on avoiding HISC. Specific recommendations aimed at giving optimized resistance to HISC are therefore emphasized.

- The use of duplex stainless steel exposed to cathodic protection involves some issues related to NDE and visual inspection. These are addressed in Section 6. For NDE reference will in general be made to relevant codes.

1.1.3 Relation to DNV-OS-F101

This Design Guideline shall to the extent possible be independent of selected design code. The aim is, however, to have a safety philosophy and design format which is consistent with DNV-OS-F101. The methods and procedures in this Design Guideline aim to give a safety level which is consistent with that required by DNV-OS-F101. Appendix A give details on how the design criteria in this guideline can be used together with DNV-OS-F101.

1.1.4 Other design codes

It is possible to apply this Design Guideline in conjunction with the following alternative design codes: ASME B31.8, ASME B31.3, ASME VIII Div. 2.

In case of conflict between requirements of this Design Guideline and a reference document, the most stringent shall apply.

1.1.5 Alternative methods and procedures

In case alternative methods and procedures to those specified in this Design Guideline are used, it shall be demonstrated that the obtained safety level is equivalent to the one specified herein and in DNV-OS-F101.

1.2 References

1.2.1 Offshore Standards

DNV-OS-F101 Submarine pipeline systems.

1.2.2 Recommended practices

The latest revision of the following documents applies:

- 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 linepipe external coating
- DNV-RP-F103 Cathodic protection of submarine pipelines by galvanic anodes

1.2.3 Certification notes and Classification notes

DNV CN 7 Non Destructive Testing.

1.2.4 Other references

- ASME VIII Boiler and Pressure Vessel Code
- ASME B31.3 Process Piping
- ASME B31.8 Gas Transmission and Distribution Piping Systems
- ASTM E112-96
- ASTM E562
- EEMUA 194:2004
- NORSOK M-001
- NORSOK M-601
- NORSOK M-630
- NORSOK M-650

Guidance note:

The latest revision of the DNV documents may be found in the publication list at the DNV website www.dnv.com.

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1.3 Definitions

1.3.1 Verbal forms

"Shall": Indicates requirements strictly to be followed in order to conform to this Design Guideline and from which no deviation is permitted.

"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.

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

"May": Verbal form used to indicate a course of action permissible within the limits of the Design Guideline.

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

1.3.2 Definitions

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

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

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

Engineering Critical Assessment (ECA): An assessment of the significance of defects.

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

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

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

Pressure, Design: This is the maximum internal pressure during normal operation, referred to 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 shut-in conditions, over the whole length of the pipeline or pipeline section which is to have a constant design pressure.

Pressure, Incidental: This is the maximum internal pressure the system is designed to withstand during any incidental operating situation, referred to the same reference height as the design pressure.

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.

Residual strain: Strain associated with residual stress.

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

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

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

Strain: Strain is defined as relative deformation associated with applied loads or residual stresses. (i.e. any strain induced during manufacture and installation shall not be included in the sum of strain). Non-linear strain is established using a non-linear stress strain curve.

Stress: Stresses should, in general, be established based on the applied loads. If specifically stated residual stresses should be included. Linear stress refer to stresses calculated assuming a linear (elastic) stress strain curve.

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

System pressure test: Final test of the complete system.

1.4 Abbreviations and Symbols

1.4.1 Abbreviations

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
SENB	Single Edge Notch Bend
SENT	Single Edge Notch Tensile
DNV	Det Norske Veritas
HAZ	Heat Affected Zone
HE	Hydrogen Embrittlement
HISC	Hydrogen Induced Stress Cracking
L	Load effect
NDT	Non-Destructive Testing
P	Production
PWHT	Post Weld Heat Treatment
SCF	Stress Concentration Factor
SIF	Stress Intensity Factor
SMTS	Specified Minimum Tensile Strength
SMYS	Specified Minimum Yield Stress

1.4.2 Symbols

ϵ_{res}	Residual strain
L_{res}	Distance from weld for which residual strains have to be taken into account in design
L_d	Design load
R_d	Design resistance
L_F	Functional loads

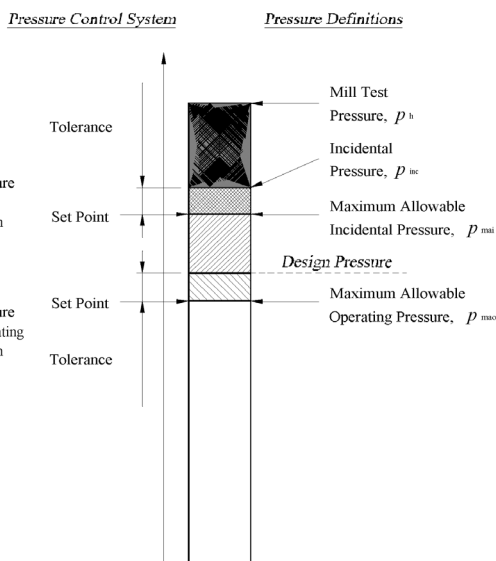


Figure 1-1
Pressure definitions

L_E	Environmental loads
L_A	Accidental loads
R	Pipe radius
γ_F	Functional load effect factors
γ_E	Environmental load effect factors
γ_A	Accidental load effect factors
γ_c	Condition load effect factor
γ_p	Pressure load effect factor.
γ_{HISC}	safety factor
R_k	Characteristic resistance
f_k	Characteristic material strength
t_k	Characteristic thickness
γ_m	Material safety factor
γ_{SC}	Safety class safety factor
σ_{HISC}	Acceptable stress in order to avoid HISC
f_y	Yield strength to be used in design
$\sigma_{d,i}$	Design values of the different principal stresses and von Mises stresses
$\sigma_{d,l}$	Design stress, longitudinal
$\sigma_{d,h}$	Design stress, hoop
$\sigma_{l,F}$	Functional stress, longitudinal
$\sigma_{l,E}$	Environmental stress, longitudinal
l_α	Average austenite spacing for field.

1.5 Acknowledgements

The following companies have contributed to the development of this guideline:

Aker Kvaerner	Shell
BP	SINTEF
Cameron	Statoil
ChevronTexaco	Technip
ConocoPhillips	Total
FMC	TWI
Hydro	Vetco

Their contribution is greatly acknowledged.

2. Design Philosophy

2.1 General

2.1.1 Objective

This section presents a summary of the safety philosophy and corresponding design format applied in this Design Guideline.

This section also provides guidance for extension of this Design Guideline in terms of new/revised criteria etc.

2.2 Safety Philosophy

2.2.1 Safety objective

An overall philosophy for avoiding HISC shall be established, planned and implemented, covering all phases from conceptual development until abandonment.

2.2.2 Systematic review

A systematic review or analysis shall be carried out at 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 damage.

2.2.3 Reliability analysis

Suitably competent and qualified personnel shall perform the structural reliability analysis related to HISC, and extension

into new areas of application shall be supported by technical verification.

As far as possible, target reliability levels shall be calibrated against identical or similar subsea designs that are known to have adequate safety. If this is not feasible, the target safety level shall be in accordance with DNV-OS-F101, Section 2.

HISC is an area where sufficient data is not available to quantify failure probability as a function of parameters such as stress, strain, potential etc. The aim is however that the design limitations set forward in this document ensure low failure probabilities.

3. Loads and Conditions (General Assessment)

3.1 General

3.1.1 Objective

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

One major part of the general assessment is to consider stresses and strains. Detailed acceptance criteria for this are given in Section 4. This section gives guidance regarding the loads that have to be considered when stresses are established.

In addition to loads and stresses the following aspects are also considered:

- During design there are certain design features that require particular attention or should be avoided.
- Coating is a major risk reducing measure that can be put in place.
- Adjusting CP potential to a less negative level may also reduce the risk for HISC.

Based on the general assessment it should be possible to assess the level of risk for different parts and components in the system. Hotspots can then be identified and treated in greater detail.

3.2 Design

3.2.1 Applicable Design codes

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 section, the most stringent requirement shall apply.

3.3 Loads

3.3.1 General

HISC is a non ductile mode of failure caused by an interaction between stresses, the cathodic protection system and a susceptible duplex stainless steel material. Stresses acting while the structure is submerged and the CP system active are therefore relevant. All load contributions causing stress and strain should 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 must be included, and that careful considerations must be given to all effects contributing to peak tensile stress. For cases with a large number of combined loads it is recommended to carry out a finite element based assessment according to Section 4.

For HISC to occur load has to be applied over a certain time. In laboratory tests, however, HISC failures have been produced in a few hours. Hence, also temporary loads shall be considered.

3.3.2 External Loads

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 are required in order to address the maximum forces that can be transferred to the component from the connecting system during installation and operation. This is particularly important for duplex stainless steel exposed to CP.

Some of the most severe duplex stainless steel HISC failures have been due to overloading. When establishing design loads for subsea systems there may be relatively high uncertainties. This is due to input parameters such as soil interaction, installation and rock dumping. An assessment of the uncertainty on the established loads should be made.

Communicating correct interface/ tie-in loads between different parts of the subsea system is crucial for a robust design of duplex stainless steel components exposed to CP. It is also important that all parties involved have a common understanding of the uncertainties related to the communicated loads. For tie-in components such as hubs and connectors it is recommended that a finite element based assessment is carried out according to Section 4.

3.3.3 Pressure containment

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

Incidental pressure should be considered unless it can be documented that it will only occur for a very short period of time.

3.3.4 Accidental loads

Subsea systems shall be protected against unacceptable damage caused by accidental loads e.g. dropped objects, fishing gear, ships, anchoring etc. Stresses caused by accidental loads should in general not be allowed to exceed the limits given in this guideline.

A brief shock load will not necessarily lead to failure. A detailed assessment is however required before allowing accidental loads to cause higher stresses/ strains than those give in Section 4.

Brief accidental loads can, however, induce deformation and build stresses into the structure.

3.3.5 Installation Loads

Installation loads in general only apply over a relatively short time. HISC may therefore not be a relevant failure mode. A detailed assessment is however required before allowing higher stresses/ strains during installation than those give in Section 4.

3.3.6 Lifetime assessment

The design shall cover the full design life of the subsea system. Relative settlement between different parts of the subsea system shall be properly assessed.

3.3.7 Fatigue

Fatigue is not treated in detail in this guideline. However, testing has shown that sharp fatigue cracks increase the susceptibility for HISC dramatically. There is likely to be an interaction between fatigue and HISC. A conservative fatigue approach should therefore be applied.

3.3.8 Residual Stresses

Residual stresses need to be taken into consideration. Residual stresses associated with welds are addressed in Section 4. If a component or design solution is likely to introduce high residual stresses special considerations are required.

Welds should not be located close to areas with stress concentrations.

3.3.9 Temperature

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

A cut off temperature above which HISC does not have to be considered has not been established. Current design criteria therefore reference temperature de-rated SMYS.

It is assumed that transient low temperatures associated with start up or depressurization does normally not need to be considered due to their short duration.

3.4 Design details

3.4.1 Sharp Defects

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 such defects. Engineering Critical Assessments show that only very small surface breaking defects can be tolerated.

If it is considered likely that sharp defects exist a detailed assessment is recommended.

3.4.2 Fillet Welds

Several of the known duplex stainless steel HISC failures are related to fillet welds. If fillet welds are used it is strongly recommended that such welds are given high attention. A detailed stress assessment should be carried out. Fillet welds are in many cases more susceptible to high ferrite contents than butt welds because of quicker cooling. It is therefore recommended to carry out separate fillet weld procedure qualification.

3.4.3 Fillets and other Stress raisers

HISC can initiate at stress concentrations due to local peak stresses. Sharp transitions with high Stress Concentration Factors (SCF) should therefore be avoided.

A finite element based assessment according to Section 4 is recommended for fillets.

3.4.4 Distance weld to stress raiser

Notches, fillets or bend curvatures should be avoided within the residual stress field close to welds (For guidance on how to assess the extent of the stress field reference is made to Section 4E). If this is not possible a finite element based assessment according to Section 4 is recommended.

3.5 Coating

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 disbonded or damaged 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).

Coating shall 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 will not occur even if the coating is damaged or removed.

Many of the reported HISC failures are in fact caused by upset loading conditions beyond the design value. Whenever practical, components in duplex stainless steel that may become exposed to high stresses during installation or in service 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 ade-

quately qualified for resistance to damage and disbondment 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.

It is recommended that the need for a detailed finite element based assessment should be considered in the following locations (See Section 4).

- All uncoated areas. (For uncoated systems such as instrument tubing a generic assessment can be made.).
- Wherever the coating is penetrated
- Wherever field joint coating is applied

3.6 Materials Selection

Even if duplex stainless steels have proven to be a cost efficient material for subsea applications there are alternative candidate materials. This includes carbon steel internally clad, austenitic stainless steels and nickel alloys. In cases where the design criteria in this Design Guideline are found to be too stringent, or where there is great uncertainty about actual loads replacing duplex stainless steel with an alternative material should be considered.

4. Design Criteria (Stress/ Strain Assessment)

4.1 General

4.1.1 Objective

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

4.1.2 Limitations

The allowable stresses and strains presented in Tables 4-1 to 4-4 presuppose that the material complies with the requirements and recommendations in Section 5.

Testing carried out in connection with the failure of the Foinaven hubs resulted in HISC failure at an applied local strain of about 0.20 - 0.24%, i.e. less than what is allowed according to Table 4-2 and 4-3. However the tested full scale hubs had an unfavourable microstructure with large austenite spacing. In addition the tested hubs had an unfavourable grain flow, mainly in the through thickness direction. For such unfavourable materials the allowable stress and strain levels in this guideline may be unconservative and special considerations would be required.

4.2 Characteristic material properties

The different material grades refer to mechanical properties at room temperature. Possible temperature effects on the material properties shall be considered at temperatures above 20°C for 22Cr and 25Cr. These properties shall be selected with due regard to material type and potential temperature-ageing effects.

HISC is not believed to be active at elevated temperatures. However, a threshold temperature above which HISC does not have to be considered remains to be stated.

Guidance note:

If no other information on de-rating effects of the yield stress exist the recommendations for 22Cr or 25Cr duplex stainless steels in Figure 4-1 below may be used.

---e-n-d---of---G-u-i-d-a-n-c-e---n-o-t-e---

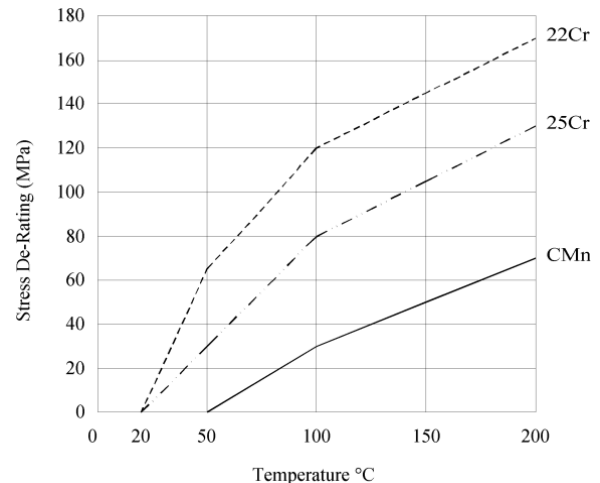


Figure 4-1
Proposed de-rating values for SMYS. For a given temperature the SMYS used in design should be reduced by the value given by the curves compared to the SMYS at room temperature.

4.3 Load and Resistance Calculations

4.3.1 Design

The design format in this Design Guideline generally supposes compliance with a selected design code.

4.3.2 Load effect calculation

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 and for each possible mode of failure to be analysed, all relevant combinations of loads which may act simultaneously shall be considered. Reference is made to Section 3.

4.4 Linear elastic stress screening criteria

The piping shall be designed according to the applicable standard (ASME B31.3, ASME B31.8, ASME VIII or DNV-OS-F101).

The stress limitations in Table 4-1a and 4-1b assumes a linear stress analysis.

SIF (stress intensification factor) for standard piping components and SCF (stress concentration factor) for non standard piping components and welds shall be included in the pipe stress analysis for both sustained (pressure and weight) and displacement (thermal and applied displacement) loads.

If the design code gives more stringent allowable stress than the limits proposed in Table 4-1a and Table 4-1b, the allowable stress of the design code shall apply. The limits in Table 4-1a and Table 4-1b also apply for hydrostatic testing and for other temporary load cases when exposed to cathodic protection.

Table 4-1a Allowable linear elastic stress for 22 Cr and 25 Cr duplex stainless steel away from welds (Outside Lres ref. Sec. 4.5.4)	
<i>Stress component</i>	<i>Allowable local and global stress ¹⁾ percent of temperature adjusted SMYS</i>
Longitudinal	80 %
Hoop	80 %
Von Mises	80 %

¹⁾ Pipe stress analysis shall include SIF and SCF for piping components. Stress limit also applies to total stress if the design is checked with linear elastic material properties according to ASME VIII Division 2 Appendix 4.

When assessing stresses near welds, the limits in Table 4-1b

apply. Both the global and local stress limits must be satisfied. Residual stresses are accounted for in the stress limits and does not need to be included separately in the stress analysis.

Table 4-1b Allowable linear elastic stress for 22 Cr and 25 Cr duplex stainless steel at welds ¹⁾ (Within L_{res} ref. Sec. 4.5.4)

Stress component	Allowable global stress ²⁾	Allowable local stress ³⁾
Perpendicular to weld direction	67 %	80 %
Von Mises	67 %	80 %

1) The stress limits are valid close to welds and within the distance L_{res}, ref Section 4.5.4. Allowable stress is expressed in percent of temperature adjusted SMYS
 2) Global stress is the stress in the net section due to the applied loads, away from stress concentrations.
 3) Local stress is the stress at a stress concentration as found in a detailed finite element analysis or by the magnification of the global stress by a SCF for the actual weld geometry.

4.5 Non-linear strain criteria

4.5.1 General

If the linear elastic stress criteria is not satisfied, the design may be checked against global and local non-linear strain criteria. The objective of the strain assessment is to ensure that the loading does not initiate significant creep in the material.

Finite element analysis using a non-linear material description including strain hardening shall be performed.

The material curve to be used shall have yield stress equal SMYS (at actual temperature), not the measured yield stress found by tensile tests taken from the component. The material curve may be linear elastic till 0.1% strain, while 80% of SMYS should correspond to 0.3% total strain and SMYS should correspond to 0.5% total strain.

Creep strain is not included in the non-linear strain evaluation.

Axisymmetric (2D) or solid (3D) finite element model may be used. Pipe misalignment at the weld connection should be included in the FE model.

4.5.2 Allowable strain away from welds

Allowable maximum principal initial strain is found in Table 4-2. The limits apply to areas not influenced by weld residual strains. A strain concentration is a local strain raiser like a fillet radius or geometrical transition.

Table 4-2 Allowable sum of initial strain from all loads (internal pressure and external loads) outside the range of weld residual strains. Allowable initial strain is the sum of elastic and plastic strain, excluding creep strain.

Location	Allowable strain at strain concentrations	Allowable strain away from strain concentrations
Outside range of weld residual strain	0.6 % strain at surface ¹⁾	0.3 % strain at surface

1) Allowable extension of strain higher than 0.3 % into the material below the surface/outer fibre of the strain concentration is maximum 5% of the wall thickness.

4.5.3 Allowable strain near welds

In the region near welds, residual strains should be taken into account. The region with residual strain near a weld is defined as a distance L_{res} on each side of the weld. A design project specific assessment should be made to establish L_{res} and the level of residual strain. Suggestions are given in Section 4.5.4 below.

Allowable strain at the vicinity of welds is found in Table 4-3.

Table 4-3 Allowable sum of initial strain from all loads (internal pressure and external loads) in the vicinity of welds. Allowable initial strain is the sum of elastic and plastic strain, excluding creep strain.

Location	Allowable strain at strain concentrations	Allowable strain away from strain concentrations
From weld to L _{res}	0.60 % - ε _{res} ¹⁾	0.50 % - ε _{res}

1) Allowable extension of strain higher than 0.60 % - ε_{res} or 0.3 % (whichever is lower) into the material below the surface/outer fibre of the strain concentration is maximum 5% of the wall thickness.

4.5.4 Assessment of residual strain

The following may be used as an estimate of the range of the residual strain field, L_{res}, beyond which the residuals are found to be negligible.

$$L_{res} = 2.5 \sqrt{Rt}$$

where R is the nominal pipe radius and t is the pipe wall thickness.

The guidance found in Table 4-4 may be used as an estimate of residual strain for girth welds in absence of measurements of the actual residual strain.

Table 4-4 Estimates of weld residual longitudinal strains.

Location	ε _{res}
At weld toe	0.15 %
From HAZ till L _{res}	0.25 %

4.5.5 Potential effect of pressure testing

If a finite element analysis including an initial residual strain distribution shows beneficial effect of pressure testing, the demonstrated effect can be used to reduce the values found in Table 4-4. If for example the initial residual strain of 0.25 % near the weld is shown to be reduced after pressure testing, the new residual strain level can be used to calculate new allowable strain level.

Allowable strain in region HAZ to L_{res} can not be higher than limits found in Table 4-2, even if the residual strain is demonstrated to be less than 0.2 % after pressure testing.

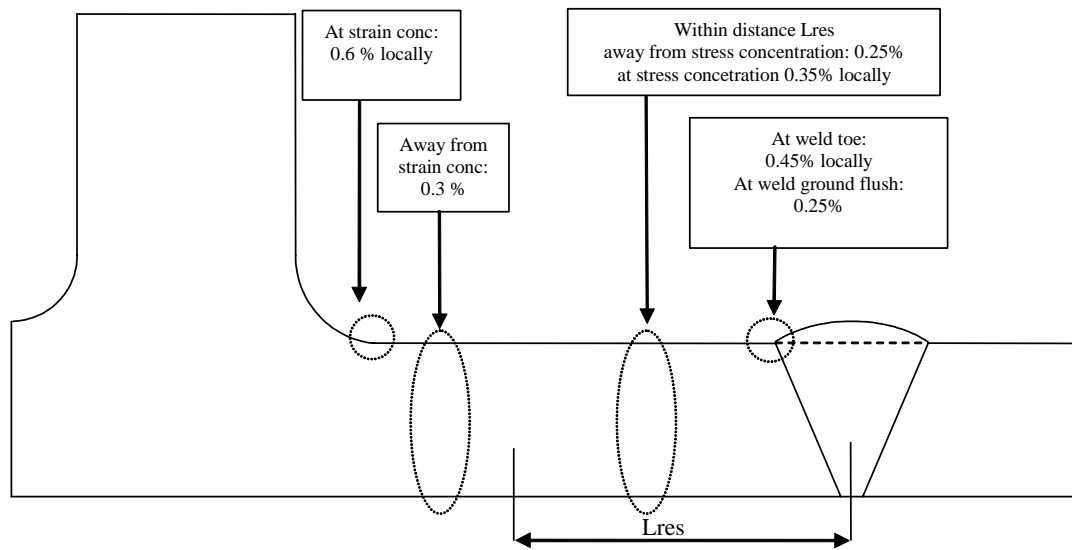


Figure 4-2
Summary of proposed allowable initial strain at strain concentrations, in regions influenced by residual strain and in regions outside the range of residuals assuming the level of residual strain indicated in Section 4.5.4.

5. Material requirements

5.1 General

5.1.1 Objective

This section specifies requirements for materials, manufacture, and testing. This includes the following:

- Limitations and general requirements related to materials that have to be fulfilled in order for the design criteria in this Design Guideline to be applicable.
- Requirements that have to be fulfilled in order to obtain what is considered to be sound duplex stainless steel material.
- Additional requirements that should be considered in order to improve the resistance of the duplex stainless steels to HISC
- Guidance related to qualification testing that may be relevant for duplex stainless steels to be used for a specific project.

5.2 Material Limitations

This Design Guideline cover material generally referred to as 22Cr and 25Cr duplex stainless steel. The limitations set on materials for which the design criteria in this specification 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.

5.2.1 Chemical composition

The chemical composition of duplex stainless steel covered by this specification should be according to DNV-OS-F101 Table 6-5, the requirements in NORSOK M-630 or another recognized standard. 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.

5.2.2 Mechanical Properties

The recommendations given in this specification are only applicable if the SMYS at room temperature is not higher than 450MPa for 22Cr duplex stainless steel and 550MPa for 25Cr duplex stainless steel.

5.2.3 Heat Treatment

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

5.3 General Requirements

Materials, welding, testing and manufacturers shall as a minimum comply with recognized standards. A number of such standards and company specific specifications exist and it is not within the scope of this specification to cover all aspects related to this issue. Recommended tests to ensure proper material properties include:

- metallography characterising the microstructure (ferrite content, intermetallic phase precipitation, austenite spacing (for information))
- corrosion test according to ASTM G 48 A
- Impact tests

Acceptable requirements for duplex stainless steels, welding, testing and documentation are specified in DNV-OS-F101.

The requirements in NORSOK (M-001, M-630, M-601 and M-650) are also considered acceptable.

5.4 Specific Requirements

5.4.1 Microstructure

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 favorable.

Ferrite content

Most specifications give requirements to ferrite content measurements according to ASTM E562. When duplex stainless

steels are exposed to CP ferrite measurements become particularly important since HISC cracks propagate in the ferrite. Such measurements should be carried out at the surface to be exposed to CP. The ferrite content should be measured in all types of welded connections (but weld, fillet weld etc.).

Austenite Spacing

Testing has shown that materials with a fine phase distribution have a greater resistance to HISC than materials with a coarse phase distribution. As a risk reducing measure requirements to measurement of austenite spacing on critical components may be specified. A tentative acceptance criteria is 30µm. Both testing and acceptance criteria shall however be subject to agreement. A procedure for measuring austenite spacing is given in Appendix B.

Grain Flow

Tests and failures have shown that adverse grain flow can give increased susceptibility to HISC. (i.e ferrite grains are orientated perpendicular to the principal stresses.). For items with an non- isotropic grain structure (i.e. forged and rolled products) the manufacturing route should be reviewed to ensure that it will not give an adverse grain flow.

5.4.2 Forgings

The fabrication of forgings should include all measures to optimise microstructure in order to reduce the risk of HISC:

- Forging of material to shape using a minimum forging ratio of 1:3 to have the metal fibers parallel to the external surface
- Avoid the precipitation of brittle phases by using sufficiently high cooling rate subsequent to forging and solution annealing. When possible the component should be rough machined as close to the final dimension as possible prior to performing the solution annealing (final heat treatment).

5.4.3 Qualification Testing

A standard test with clearly defined acceptance criteria to test the susceptibility of duplex stainless steels exposed to CP has not yet been established. It is therefore not reasonable to specify any mandatory testing. One of the main goals of the ongoing research is to investigate various types of test procedures.

Guidance note:

If a projects 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. This in order to be able to compare the results from the 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.

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6. Non Destructive Testing

6.1 General

This section gives recommendations related to Non Destructive Testing of duplex stainless steels. This includes:

- Surface testing of base material and welds

- X-ray inspection of base material and welds
- Ultrasonic inspection of base material and welds.

The reason for including these recommendations in this document is that 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 as low as 0.01 mm. It has therefore been concluded that there is a high vulnerability to defects in general, and surface breaking defects in particular.

6.2 Extent of NDT

It is recommended that 100% surface testing is carried out on welds and components. It is recommended that the volume of the material in all components is inspected 100% by ultrasonic inspection. X-ray and Ultrasonic volumetric inspection of welds and base materials both have their weaknesses and strengths. As a general rule the best result is achieved if inspection 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.

6.3 Surface Testing

6.3.1 Referenced Specifications

Penetrant testing: DNV classification Note No.7. DNV-OS-F101, Appendix D, B100 & B500

Eddy current testing: DNV classification Note No.7. DNV-OS-F101, Appendix D, B100 & B600

6.3.2 Specific recommendations

Surface testing should be performed in the first instance as a supplement to radiographic and ultrasonic inspection for welds and forgings.

6.4 Ultrasonic Inspection

6.4.1 Referenced Specifications

Weld examination: DNV classification Note No.7

Forging examination: No totally relevant codes or standards are known.

6.4.2 Specific recommendations

The following recommendations apply to ultrasonic inspection of duplex stainless steel in general:

- Use longitudinal waves (in general avoid shear waves)
- Use focused probes, as appropriate
- Avoid 'skipping' (i.e. reflection from the back wall)
- Use multiple probe angles, from 'creep' to normal probes (with machining of weld surfaces)
- Compensate for variation in attenuation
- Avoid the use of prefabricated amplitude-distance diagrams (DGS or AVG)
- Use reference blocks of the actual material to be tested, if relevant with weld(s)
- Use qualified ultrasonic operators (e.g. according to EN473/Nordtest Level 2 with supplementary qualification 'Welded joints in stainless steel')

The following recommendations apply to ultrasonic inspection of duplex stainless steel welds:

- Characterization of indications in welds should be in accordance with EN 1713 provided that limitations in the suitability of the standard as stated in Chapter 1 of the Standard are observed.
- The ultrasonic technique used should be qualified using the approach given in Nordtest TechReport 394; Guidelines for NDE Reliability Determination and Description or ENIQ document EUR17299; European Methodology

- for Qualification and relevant Recommended Practices
- Ultrasonic examination of duplex stainless steel and dissimilar metal welds is a very cumbersome and meticulous task, but can be done with care taken
- Supplementary radiography should be used to ease interpretation of findings (e.g. interrun lack of fusion or volumetric defect; or possible geometric distortion)

The following recommendations apply to ultrasonic inspection of duplex stainless steel forgings of a size permitting ultrasonic inspection:

- Forged components are often a larger ultrasonic challenge than other products in duplex stainless steels due to larger, and varying, grain sizes and heavy dimensions
- Ultrasonic testing should, in general, be done from all accessible surfaces with normal, longitudinal angle beams and creep waves. Flat bottom holes (FBH) are normally used as reference reflectors (surface notches for creep waves)
- Additional ultrasonic examination after machining, to cover thinner sections which may have a higher stress concentration and thus having different or more stringent acceptance criteria, is recommended.
- The ultrasonic testing should be supplemented by surface NDT (penetrant or eddy current examination).

6.5 X-ray inspection

6.5.1 Referenced Specifications

DNV classification Note No.7.

6.5.2 Specific recommendations

Radiography should be performed as X-ray preferably utiliz-

ing Constant Potential (CP) equipment and ultra fine grained film with lead screens and lead backing to avoid back scatter.

If X-ray cannot be used due to material thickness or limitation on access, gamma ray may be used provided the selection of source type and size, film, screens and backing are selected to give optimum results. To ensure optimum possibility for detection of lack of fusion type defects in welds multiple exposures with the X-ray beam parallel to the fusion lines should be performed. It should be noted that volumetric defects such as in line porosity may mask the more detrimental planar defects. Supplementary ultrasonic inspection is recommended when multiple exposures are made and should be mandatory if only single exposures are made.

6.5.3 Visual Inspection

For design according to this Recommended Practice there will in general have to be put great 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 design

It may further be relevant to carry out a visual inspection of weld root penetrations where accessible.

7. References

- /1/ P. Woollin and A. Gregori, TWI, OMAE 2004-51203, Avoiding hydrogen embrittlement stress cracking of ferritic austenitic stainless steels under cathodic protection.
- /2/ Taylor, Pendlington and Bird, BP Amoco, OTC 10965, Foinaven super duplex materials cracking investigation, 1999.

APPENDIX A ADAPTION OF SCREENING CRITERIA TO DNV-OS-F101 DESIGN

A.1 Design format in DNV-OS-F101

The design format in DNV-OS-F101 is based on the limit state methodology expressed on a load and resistance factor design (LRFD) format.

The fundamental principle of the LRFD format is to verify that design loads do not exceed design resistance for any of the considered failure modes. The general format is given by:

$$f\left(\left(\frac{L_d}{R_d}\right)_i\right) \leq 1 \quad (1)$$

Where L_d is the design load effect, R_d is the design resistance and the index i denotes the different loading types that enters the design criterion. A design load effect is obtained by multiplying a characteristic load effect by load effect factors:

$$L_d = L_F \cdot \gamma_F \cdot \gamma_c + L_E \cdot \gamma_E + L_A \cdot \gamma_A \cdot \gamma_c \quad (2)$$

where

L_F, L_E, L_A are the functional, environmental and accidental loads respectively

$\gamma_F, \gamma_E, \gamma_A$ are the functional, environmental and accidental load effect factors respectively

γ_c is the condition load effect factor. For HISC applications this factor shall not be taken less than unity.

The load effects shall include any non-linear effects and stress or strain concentrations if relevant.

A design resistance is obtained by dividing the characteristic resistance based on characteristic variables by resistance factors

$$R_d = \frac{R_k(f_k, t_k)}{\gamma_m \cdot \gamma_{SC}} \quad (3)$$

where

- R_k is the characteristic resistance
- f_k is the characteristic material strength
- t_k is the characteristic thickness
- γ_m, γ_{SC} are the partial resistance factors

For one loading type, this may be illustrated as shown in Figure A-1

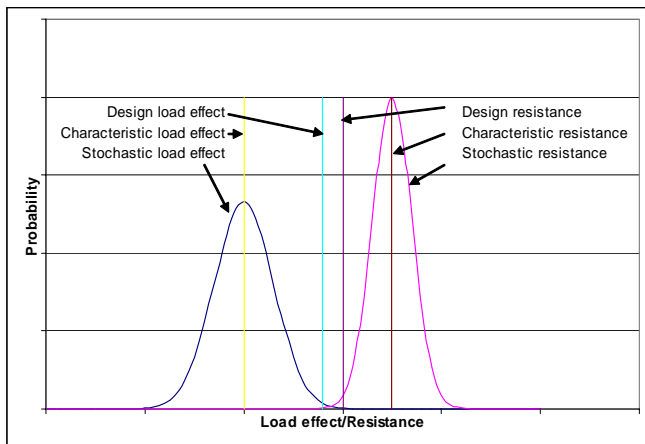


Figure A-1
Illustration of the load and resistance; characteristic values, design values and associated uncertainties

Note that even though both the characteristic load effect and characteristic resistance has been drawn as the mean value, this may not be the case. Hence, a design criterion must be based on a well defined characteristic load effect, the load effect factors to be applied, the definition of characteristic capacity and applicable partial resistance factors.

In DNV-OS-F101 the functional loads are defined as the most probable maximum value in the considered time period (DNV-OS-F101 Section 4 B201) and the associated design value is 20% or 10% higher depending on whether system effects are present or not. There is no general definition of the characteristic resistance and the definitions are specific for each failure mode giving the target safety level with the determined partial safety factors.

A.2 Recommendations on design for Hydrogen Induced Stress Cracking

A.2.1 Characteristic HISC resistance

The characteristic resistance for HISC is given in Section 4 Tables 4-1 to 4-4.

A.2.2 Design criterion

It is recommended that the load effects and resistance is calculated as per DNV-OS-F101. The following design criteria shall then be fulfilled for all expected design load effect combinations:

$$\sigma_{d,i} \leq \frac{\sigma_{HISC}}{\gamma_{HISC}} \quad \text{Load Controlled condition} \quad (4)$$

Where $\sigma_{d,i}$ are the design values of the different principal stresses and Von Mises stresses (i.e. each principal component as well as the Von Mises stresses shall meet this requirement) and γ_{HISC} is equal to unity. The principal directions are normally identical with the longitudinal (l) and the circumferential (h) stresses and shall be calculated as:

$$\sigma_{d,l} = \sigma_{l,F} \cdot \gamma_F + \sigma_{l,E} \cdot \gamma_E \quad (5)$$

$$\sigma_{d,h} = \sigma_h \cdot \gamma_p$$

The following shall be noted:

- If $\sigma_{l,E}$ reduces the combined stress it can be ignored.
- Any stress concentrations shall be included in the stress components
- The product of the load effect factors, shall not be taken less than unity.

The characteristic internal pressure as well as the characteristic wall thickness for stress calculations is given in Table A-1.

A.2.3 Discussions

The system test will normally be the governing criterion when the HISC criterion is added. The incidental to design pressure ratio is 110% and the test pressure is 5% above the incidental pressure

In practice, the environmental load effect will most likely be negligible. Equation (5) may then be simplified applying a unit load effect factor of 1.1 on all components, documented by simple hand calculations, possibly with a slight modification on the acceptance criterion (i.e. slightly less than 80%).

In case the system pressure test is not governing, additional benefit may be taken from the fact that the susceptibility is less

at higher temperatures.

Again, as stated in the introduction, it is strongly recommended to specify the HISC criterion as a separate limit state.

	<i>Characteristic wall thickness¹</i>	<i>Load Combination²</i>	<i>Internal pressure</i>	<i>Comment</i>
Pressure Containment	t ₁	-	Local incidental	Pressure only
Other	t ₂	A	Local design	When system effects are present. Typically only installation
	t ₂	B	Local Design	Always checked
1) Ref. DNV-OS-F101 Section 5 C300				
2) Ref. DNV-OS-F101 Table 5-6				

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APPENDIX B

PROCEDURE FOR ASSESSMENT OF AUSTENITE SPACING

B.1 Specimen sampling

B.1.1 Base material

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.

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 is relevant (Typically if hoop stresses are dominant).

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.

For components with variable wall thickness (i.e. forging, castings) the austenite spacing shall be measured in sections with a wall thickness which is comparable to the max 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.

B.1.2 Welds

In order to make an assessment of a weld, a through thickness macro should be prepared. The austenite spacing should be measured in a plane representing the likely cracking direction, (i.e. generally in the through thickness direction). Austenite spacing measurements should be carried out at both surfaces of the weld. If one of the surfaces will not be exposed to cathodic protection, austenite spacing measurements may be omitted at this surface.

B.2 Microstructure assessment

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 phase or particles (e.g. sigma phase, carbides, nitrides) should be reported. All reported findings should be documented with micrographs.

B.2.1 Base Material

For base material the following should be reported:

- If the austenite appears to be homogeneously distributed in the samples.
- If equiaxed austenite phases present in “clusters” between considerably larger austenite islands are observed. Such phases may be ignored during austenite spacing measurements.
- If individual large ferrite units are observed.

B.2.2 Welds

For welds the same assessment as for base material should be carried out. In addition it should be reported if a ferrite rich

band is observed in the heat affected zone.

In many cases it is possible, based on a general assessment, to conclude that the austenite spacing in the weld metal is considerably finer than that of the base material. If this is the case, it should be considered whether measurement of austenite spacing of the weld can be omitted.

B.3 Measuring the austenite spacing in base material and welds

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 done according to generally recognized industry practice. Requirements relevant for measurement of austenite spacing are given in paragraph 17 of ASTM E112-96.

B.3.1 Line intercept measurement with individual measurements

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. This is the type of measurement previously applied by TWI /1/ and other operators. It is therefore considered to be the current industry practice.

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.

Measurements should be carried out in 4 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 4 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 B-2).

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 great emphasis should be put on the general assessment of the microstructure (Section 5).

B.3.2 Statistical analysis

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 4 fields. The standard deviation “s” obtained using these 4 values is then calculated (eq. 13 in /2/). This standard deviation is then used to calculate the 95% confidence interval “95% CI” (eq. 14 in /2/) and the relative accuracy “%RA” (eq. 15 in /2/). “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%. For four fields the value “t” in equation 14 of Ref /2/ is 3.

B.4 Figures

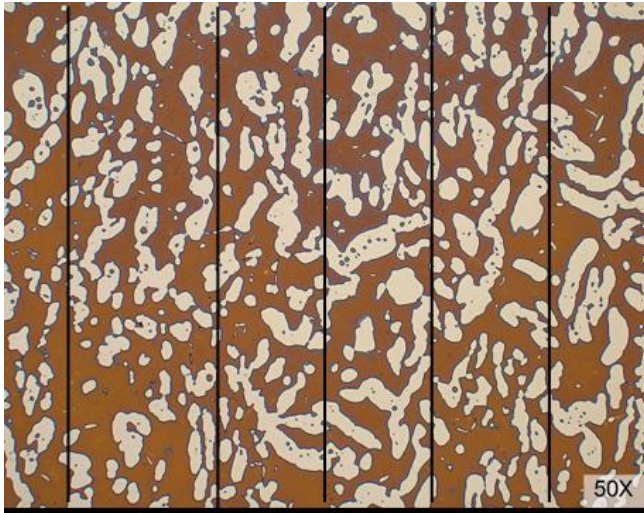


Figure B-1
Typical micrograph with lines to be used to measure austenite spacing.

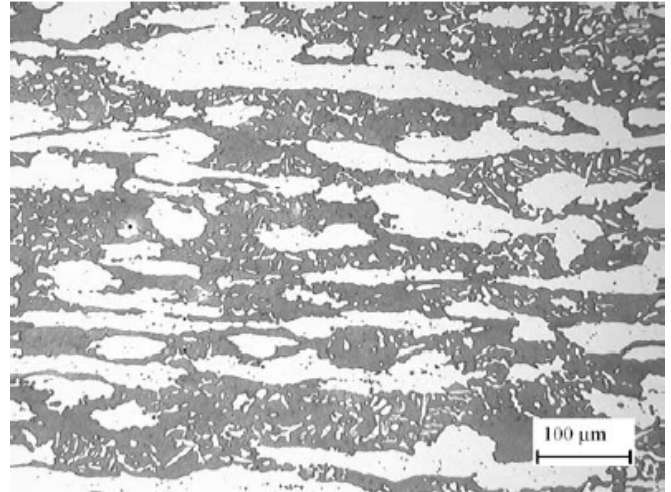


Figure B-2
Micrograph showing fine austenite phases present in "clusters" between considerably larger austenite islands (Ref. /1/).

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