Intergranular stress corrosion cracking of austenitic stainless steels – is it still an issue?

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Abstract

Environmentally assisted intergranular cracking (EAC) in austenitic stainless steel piping in nuclear power plants started with extensive cracking in boiling water reactors in the 80’s. These events initiated extensive research programs, which led to numerous mitigation steps and lessons learned. The research, development and mitigation actions dealt with new material(s), new welding techniques and new water chemistry strategies as well as on achieving a mechanistic understanding. The actions have been mainly, but not totally, successful, and research is still ongoing and needed. This paper gives a review on EAC in stainless steels in LWR’s and is a personal opinion of where research and measures are especially needed.

Keywords: “review”;“austenitic stainless steels”;”intergranular stress corrosion cracking”;”IGSCC”; “BWR”;”PWR”

Introduction

Austenitic stainless steels have rendered extensive use because of their good performance in corrosive environments in addition to their excellent ductility, formability, toughness and weldability. The good corrosion resistance of austenitic stainless steels is mainly due to chromium alloying, resulting in a protective, chromium-rich passive film on the material in many environments. Molybdenum, used as an alloying element in Type 316 stainless steels, further increases the corrosion resistance. Chromium and molybdenum are, however, both ferrite forming elements, and to maintain a fully austenitic structure, a balance between austenite stabilizing elements (C, N, Ni, Mn and Co) and ferrite stabilising elements (Cr, Mo, Si, Ti, Nb, Al, V and W) in solution must be established [1]. To compensate the molybdenum addition in Type 316 type stainless steels, the amount of nickel is increased. In materials for nuclear environments, the cobalt content is kept as low as possible (<0.02%), due to its strong influence on radioactivity build up.

Stress corrosion cracking (SCC) is taken into account in the design codes for light water reactors (LWR’s, i.e., boiling and pressurized water reactors or BWR’s and PWR’s) through a statement that SCC should not occur [2] or that only materials with known, good behaviour shall be used, with specification on carbon content, heat treatment, grinding etc. [3]. Still intergranular stress corrosion cracking, IGSCC, is by far the largest damage mechanism for austenitic stainless steels in oxidizing BWR conditions and an increasing amount of cases are reported in PWR’s [4-8].

Several factors affect IGSCC, one of them being sensitisation. Sensitisation is a result of nucleation and growth of chromium-rich carbides on grain boundaries causing grain boundary chromium depletion due to faster chromium diffusion along grain boundaries. Chromium depleted grain boundaries are prone to corrosion, and in combination with a large enough
stress, to intergranular stress corrosion cracking. All measures to prevent sensitisation are therefore taken in all steps of component manufacturing and plant operation. Concerning the chemical composition, this can be done by reducing the carbon content to levels below 0.03%, as is done in Types 316L, 316LN and 316NG stainless steels, where the carbon content typically is in the order of 0.02%. Since carbon is a strengthening element, nitrogen is added to these steels to achieve good mechanical properties. Nitrogen reduces chromium-rich carbide formation, a concept which is utilized in the French RCCM norms, which allow a carbon content of 0.035% in their nitrogen-strengthened Type 316 stainless steel with ≤ 0.08% N. The other approach to avoid sensitisation is to tie up the carbon into precipitates. This is utilized in stabilised stainless steels, which are of two main categories, i.e., titanium and niobium stabilised stainless steels, Type 321 and 347, respectively. To ensure, that the carbon is tied into Ti(C,N) or Nb(C,N) precipitates, a big enough stabilisation ratio is required [9].

Good corrosion resistance is ensured by restricting the amount of harmful elements, especially sulphur and phosphorus, which may cause intergranular corrosion when segregated to grain boundaries. Several standardised grain boundary corrosion tests, such as the Strauss test [10] and the EPR, i.e., the electrochemical potentiokinetic reactivation test [11] are employed routinely as part of acceptance tests for materials and components.

In addition to compositional, mechanical and corrosion resistance requirements, several other requirements are put on austenitic stainless steel materials for nuclear components. These include, e.g., requirements on grain size. A small enough grain size is needed to enable reliable non-destructive inspection requirements using ultrasonic techniques. A common requirement is that the grain size must not exceed ASTM number 4.0, which corresponds to an average grain size of 90 µm. The grain size of stabilized stainless steel components is typically smaller than this.

**Components Made of Stainless Steels in BWR’s and PWR’s**

Austenitic stainless steel is the main construction material in nuclear power plants due to its good corrosion resistance, ease to manufacture different shapes and good weldability. In BWR’s, stainless steels are used for piping and structures inside the pressure vessel, including the core shroud (which separates the primary water upward flow through the core from the downward flow in the annulus), the core plate (which supports the bottom of the fuel), the top guide (which aligns the top of the fuel bundles), the shroud dome, the steam separators, etc. Austenitic stainless steel is also largely used for other components such as pumps, valves, shafts, sleeves and in auxiliary systems such as water tanks etc.

The material choices for PWR’s are essentially the same. The steam generator tubes are made of Ti-stabilized stainless steel in the Russian designed VVER’s, which are PWR’s with slightly different water chemistry and horizontal instead of vertical SG’s, as in Western PWR’s. The steam generator tubes in Western PWR’s are made of iron-based Alloy 800 or nickel-based materials (Alloy 690, earlier Alloy 600). Further, both the steam generator vessel and the pressurizer are clad with austenitic stainless steel.

**Welding of stainless steels**

Stainless steels are generally welded with a slightly over-alloyed filler metal to ensure good corrosion resistance of the final joint. The weld shall contain a small amount (more than 3% but less than 10%) of δ-ferrite to avoid solidification and liquation cracking [12].
induces residual stresses, which together with the operational stresses enhance crack initiation and growth. The aim is, naturally, always to minimize the residual stresses by proper choice of welding parameters, by securing a good fit between the parts to be welded, etc. The use of a narrow-gap welding technique has increased remarkably during the last decades. The narrow-gap welding method has many advances as it results, e.g., in a lower level of residual stresses, a reduced weld volume, a narrower heat-affected zone (HAZ) with lower risk for sensitisation and less grain growth [13].

**Stress Corrosion Cracking**

Stress corrosion cracking is a failure mode caused by a combination of a susceptible material, stresses and an aggressive environment, Figure 1. There are two modes of stress corrosion cracking in austenitic stainless steels, namely intergranular and transgranular stress corrosion cracking, i.e., IGSCC and TGSCC. Intergranular stress corrosion cracking in austenitic stainless steels is the major failure mode in BWR’s, while it has typically not been considered as a plausible failure mode in PWR primary water under normal operation conditions. In a plenary speech on EDF’s strategy for plant life management, SCC is considered for internals in addition to irradiation assisted SCC, but only thermal ageing for the primary piping [1]. However, the number of IGSCC cases in PWR’s has increased by time, showing that PWR’s are not totally immune to IGSCC.

Most TGSCC cases are due to chloride-induced SCC. TGSCC is, and should be, rare in the primary system, and the failure cases are typically observed in auxiliary systems, although still occurring, and shall therefore not be forgotten in plant life management.

![Figure 1](image.png)

Figure 1: The classic presentation of stress corrosion cracking includes the three circles: material, environment and stress [15].

**Intergranular Stress Corrosion Cracking in BWR Environment**

In the following the main factors affecting IGSCC in BWR environment are reviewed, i.e., degree of sensitisation, deformation, electrochemical corrosion potential (ECP), water purity and stress. Also several other parameters affect IGSCC susceptibility, and a short list chapter is included on these later in the paper.
Degree of sensitisation

Sensitisation is the result of nucleation and growth of chromium-rich carbides $\text{M}_2\text{C}_6$ at the grain boundaries, which results in a depletion of chromium at the grain boundaries due to faster diffusion rate along the grain boundaries compared to that within the grain interior. Chromium-rich carbides form within the temperature range of ~500 - 750°C, but continue to grow down to much lower temperatures. Sensitisation can therefore occur as thermal sensitisation during heat treatment and welding or as low-temperature sensitisation during long-time exposure to LWR temperatures, below the chromium-rich carbide precipitation temperature [16]. In the latter case, the nucleation of carbides must have occurred previously, and the nucleated carbides grow during the long-time exposure and deplete the grain boundaries of chromium. The degree of sensitisation is typically measured using the EPR test, which is sensitive to the area, where the grain boundary chromium content is below about 15%, and is, thus, not a true measure of the grain boundary chromium content.

The time for carbide precipitation increases as the carbon level decreases as seen in Figure 2 (a). Nitrogen alloying delays carbide precipitation, Figure 2 (b), while deformation accelerates diffusion and precipitation. The obvious remedy to avoid sensitisation is, thus, to decrease the amount of free carbon, as explained earlier, by reducing the carbon content, increasing the amount of nitrogen or by tying carbon to Ti- or Nb-carbides and by restricting the degree of deformation.

IGSCC in sensitized stainless steels occurs typically in the weld heat-affected zone at a distance of 4-8 mm from the fusion line, at the location where a high degree of sensitisation combined with high residual stresses results in most severe conditions for IGSCC. The typical location of IGSCC is different in non-sensitized stainless steels, where IGSCC occurs very close to the fusion line, within the first few grains, where the degree of residual strain from welding is largest.

Figure 2: Time–temperature–precipitation diagram for stainless steels with different carbon contents (a) [6], and effect of nitrogen on precipitation of $\text{M}_2\text{C}_6$ in a 0.05C-17Cr-13Ni-5Mo stainless steel (b) [1].

Deformation

Deformation increases the susceptibility of stainless steels to IGSCC, in sensitized as well as in non-sensitized stainless steels, where the role of strain is decisive. Deformation occurs as bulk cold work from rolling, bending, grinding etc., as surface cold work from machining, grinding etc. and from weld shrinkage from welding. Weld shrinkage can lead to up to 25% equivalent room temperature strain in the weld heat-affected zone, Figure 3. The highest
degree of deformation occurs very close to the fusion boundary, and this is also the location of observed IGSCC cracking in non-sensitized stainless steels pipes [17-20]. The importance of cold deformation in IGSCC is seen in Figure 4. Deformation is estimated to be the main affecting parameter in ~50% of all IGSCC cases covered in the survey (including sensitized and non-sensitized stainless steels). The effect of deformation has been extensively studied using bulk-deformed materials [21-30], and the results show a correlation between IGSCC crack growth rate (CGR) and yield strength, Figure 5.

Much effort is nowadays put on deformation in terms of restrictions on bulk and surface deformation and on development of sophisticated surface treatment procedures to remove surface cold work at critical locations [31-33]. Application of narrow-gap welding results in both a decrease of the degree of deformation in the HAZ as well as in lower residual stresses. However, if an IGSCC crack would initiate and grow next to a narrow-gap weld, the crack path would be perpendicular to the main stress, and not inclined, as in V-groove welds. It should be pointed out that some components, such as bolts, can be made of intentionally cold-worked stainless steel to increase the material strength.

![Figure 3: Deformation vs. distance from the weld fusion line in various stainless steel weld HAZ's. Deformation is expressed in terms of equivalent tensile strain at room temperature, and results from weld shrinkage strains during welding [23].](image)

![Figure 4: Cause of IGSCC in Swedish nuclear power plants. Cold work is the biggest single parameter affecting IGSCC [34].](image)
Environment

As earlier mentioned, one of the main reasons for the good behaviour of austenitic stainless steels in LWR conditions is the formation of a protective passive film in high temperature water (around 300°C). The oxide film formed in high temperature water has a double-layered structure. The inner layer grown on the metal surface consists of a chromium-rich spinel or magnetite and is covered by an outer layer of magnetite or Fe-Ni spinel precipitated from the aqueous phase [35, 36]. The double layer oxide structure forms so that faster diffusing elements pass through the inner layer to the outer layer while the slower diffusing elements, such as chromium, remain in the inner layer and therefore the outer layer contains mainly of iron and the inner layer is enriched in chromium. Although consensus is not yet reached on the mechanistic details for corrosion and stress corrosion cracking in LWR-environments, breaking of the passive film is generally considered to be of major importance due to the fact that if the oxide film ruptures, the corrosion rate is high until repassivation has occurred [21, 22, 37].

The crack growth rate of IGSCC is highly dependent on the oxidizing power of the environment, i.e., the electrochemical corrosion potential, Figure 6. The corrosion potential increases as the oxygen content increases in the high temperature water, but it is not a linear relationship, and small changes in oxygen concentration can result in large changes of ECP and CGR. Important to notice is that the correlation between CGR and ECP is different for sensitized stainless steels and deformed, non-sensitized stainless steels, which show much higher CGR’s as compared to sensitized materials at low potentials (although lower than at high ECP).

Over the last 40 years significant chemistry control changes have been made to reduce the frequency of, or to mitigate cracking mechanisms. The chemistry regimes include the transitions from the original BWR regime of Normal Water Chemistry (NWC), followed by Hydrogen Water Chemistry and moderate Hydrogen Water Chemistry (HWC-M), original (classic) Noble Metal Chemical Applications (NMCA), On-line NobleChem™ (OLNC), and Low-Temperature NobleChem™, applied to recirculation piping surfaces [38]. The ECP in a BWR recirculation circuit during normal operation and using normal water chemistry (NWC), i.e., ~200 ppb oxygen is above 100 mV SHE. The ECP is still higher in the core due to radiolytic decomposition of water forming hydrogen peroxide, H₂O₂. The ECP is remarkably
lower in plants using either hydrogen water chemistry (HWC), where 40 – 250 ppb hydrogen is added to the feed water or noble metal chemistry (NMC), where a small amount of platinum is added to the reactor water, either at about 130°C during start-up or during full power operation (OnLine NobleChem™), creating an electrocatalytic surface layer [39, 40]. The ECP of the buffered PWR environment is in the lower range of the ECP curve, i.e., about -600 mV_{SHE}. The trend, especially for the US BWR fleet is towards HWC and NMCA. None of the US BWR plants operate on normal water chemistry, and 75% apply NMCA [41]. The majority of the European BWR’s operate on NWC.

Water purity has a profound effect on both crack initiation and CGR in oxidising environments. The main concerns are chlorides and sulphates for SCC and additionally copper for pitting corrosion (Cu also has a synergistic effect on SCC). Already levels in the ppb-range of sulphates and/or chlorides increase the IGSCC susceptibility. Power plants monitor the conductivity, which is a mirror for the water purity, on-line and analyse the amounts of impurities on regular basis from grab samples. The conductivity of BWR primary water of today has been reduced from a typical range of about 0.4 µS/cm in the 70’s to 0.1 – 0.2 µS/cm (the conductivity of theoretically pure water is 0.056 µS/cm).

Dissolved oxygen is consumed inside cracks and crevices, and the local ECP is reduced to low levels, creating a potential gradient between the outer surface and the crack tip. This results in migration of anions into the lower potential area, which results in very high anion levels inside the crack despite of low levels in the surrounding environment [42]. Further, the local environment in a crack can remain aggressive for long times after, e.g., short periods of higher impurity levels in the bulk environment due to the potential gradient.

It is not only the environment during steady-state operation that needs attention, but also the environment during shut-down, downtime periods and during start-up. The possible role of these will increase with plant age and amount of shut-downs and start-ups. Further, pre-passivation of the primary system will affect the oxide layer on the surfaces, and have an influence on the later behaviour of the system, including the IGSCC susceptibility. The optimisation of pre-passivation during hot functional tests is an area which deserves more focus [43].
Figure 6: Summary of crack growth rates of sensitized stainless steels versus corrosion potential [26], ECP (a) and for non-sensitized stainless steels versus solution conductivity (b) [21]. The prediction curves for different water conductivity levels are according to the PLEDGE model (Plant life extension and diagnosis by GE).

Stress

The stresses causing IGSCC are a combination of residual and operational stresses, although the first is considered more decisive in IGSCC failures. This is because operational stresses are kept low by design and components are usually designed to operate below 80% of their yield strength. The crack growth rate of intergranular stress corrosion cracks increases with increasing stress intensity factor (K), Figure 8. The effect of stress intensity on CGR varies depending on material and environment. Knowledge on the dependency between K and CGR is very important for structural integrity calculations, which are made to show that flaws, either postulated or detected using non-destructive inspections, are tolerable and do not pose a safety risk. Huge efforts have been put on production of high-quality laboratory CGR data and efforts are still ongoing. Approved relationships (i.e., agreement reached between national safety authority and plant operators) are called disposition lines, and examples of published lines are shown in Figure 7 [45-47].

Several methods to mitigate IGSCC by reducing the stress have been applied over the years, such as last-pass heat-sink welding, mechanical stress improvement and weld overlay cladding [15]. All these aim at producing a compressive stress state in the HAZ. However, these methods are usually applied as temporary remedies although they have also been applied as a final remedy for dissimilar metal welds to protect from cracking in Ni-based weld metals.
Measurement of residual stresses is an area of increased focus nowadays, and lack of knowledge can result in excessive under- or over-conservatism in design and in structural integrity calculations. Also other stress-related factors affect IGSCC; such as vibratory loading, thermal loads from, e.g., stratification as well as load cycles during shut-downs and start-ups. Power up-rates typically reduce the design stress margin, and extensive structural integrity calculations are done to assure that the margin is still acceptable. Also load-follow increases the amount of loading transients, which undoubtedly will have a detrimental effect on IGSCC resistance, but no quantitative data is available on what the effect is. Much effort was earlier put on defining the \( K_{\text{ISC}C} \); i.e., the stress intensity, below which stress corrosion cracking would not occur. With improved laboratory testing techniques lower and lower \( K_{\text{ISC}C} \) values have been measured and a true threshold value may not exist.

Another area of improvement is surface treatments to reduce the residual stresses at the surfaces and thereby also the initiation susceptibility. Laser peening, fibre laser, water jet peening, low plasticity burnishing and electrochemical polishing/surface treatments are developed and used, for e.g. core shrouds in BWR’s and bottom-mounted instrumentation penetrations in PWR’s in Japan. Although the importance of the surface condition has been recognised, commonly accepted guidelines on best practises and rules are still lacking [44].

Figure 7: CGR versus stress intensity factor \( K \) using different CGR algorithms for stainless steels in BWR environments. The curves in NWC environment are drawn with solid lines, and those for HWC with dashed lines [47].

Figure 8: Surface stresses on Type 304 stainless steel with or without laser peening [33].
Systematic investigations on factors affecting initiation are ongoing, but is still in its infancy. Numerous parameters are recognised and taken into account in design, manufacturing, assembly and operation. Kilian emphasise design and manufacturing in her modified initiation graph, Figure 9 [44]. Doing it right from the beginning reduce the future risk for crack initiation and growth. However, much R&D is still needed to quantify different parameters and then reach a consensus on optimisation of these parameters, taking also the industrial realities into account. That dynamic loading is essential for crack initiation has been recognised in laboratory experiments and concluded from field experience. This will inevitably also results in an increasing risk for crack initiation with plant lifetime, especially for plants which operate under load follow.

Figure 9: Elementary phases included in the initiation process [44].

Mechanistic understanding

Research on stress corrosion cracking mechanisms is an ongoing effort since the 1930’s, when the first cases of SCC in austenitic stainless steels were discovered in the petrochemical and paper industries, without a full consensus on the mechanism [49]. The proposed mechanisms for IGSCC include slip-dissolution, slip-oxidation, internal oxidation, hydrogen-assisted cracking, film-induced cleavage, vacancy injection, selective dissolution - vacancy creep mechanisms and many more. Localisation of plastic deformation and the interactions between oxidation and strain localisation are most probably playing the key role in cracking of cold-worked stainless steels. Localisation of deformation, again, is affected by numerous phenomena, such as hydrogen effects, dynamic strain ageing, environmentally enhanced creep, dynamic recovery and relaxation. A detailed description of possible mechanisms is not included in this paper, but the readers are referred to the literature for details [49-67].

According to the most accepted mechanism for IGSCC, the slip-dissolution mechanism, crack initiation is a result of local corrosion at the emerging slip planes, i.e. a result of breaking of the protective passive film. Crack growth results of the plastic straining at the crack tip, which ruptures the protective, but brittle oxide film that forms at the crack tip environment. Once the oxide film is ruptured, the crack advances by anodic dissolution of the bare metal matrix. Repassivation of the bare metal surface will start immediately when the oxide film rupture has occurred, and will hinder further dissolution resulting in a step-wise crack growth. The rate determining factors are the crack tip strain rate, the oxide film fracture strain and the
dissolution and repassivation rates, which again can be affected by several of the above mentioned phenomena. Lately, the effect of deformation path has been investigated, and the results show a clear effect of it, i.e., a more complex strain path increases the stress corrosion susceptibility of stainless steels to stress corrosion cracking in PWR environments [55, 56].

Components at risk and plant operation experience in BWR environment

The earliest incidents of SCC in BWR’s occurred in stainless steel fuel cladding, before zirconium alloys were used [68]. After that, the cases of IGSCC in stainless steel materials have occurred in a rather logic manner if one considers factors of susceptibility. In the 1970’s, IGSCC plagued high-carbon (>0.035% C) Type 304 stainless steel in the BWR’s and caused a clear reduction in capacity factors. In early 1990’s, the first reports on IGSCC in Ti-stabilised stainless steels occurred, and soon after that, cracking in RBMK-plants, with oxidising environment and also using Ti-stabilised stainless steel, were reported. In the 1990’s, the first reports on IGSCC in non-sensitised, deformed stainless steels occurred in BWR’s, followed by the first public reports on IGSCC in PWR plants. Large efforts have been undertaken to minimise the risk for IGSCC and the amount of cases has reduced remarkably, but IGSCC is certainly still a potential failure mode, which requires still improvements in manufacturing quality control, plant operation, inspection and mechanistic understanding.

Early IGSCC cases in sensitised Type 304 stainless steel

Cracking was first observed in the recirculation and water clean-up systems in pipes with small diameter and later also in larger diameter pipes. The material was mainly Type 304 with a high carbon content of ~0.06%, used in the beginning of NPP designs. A high carbon content was adopted to increase the strength of the material, without fully realising the risk for sensitisation, and especially not the low-temperature sensitisation. Due to the large efforts to solve the problem, including development of Type 316NG, narrow-gap welding technique as well as low potential water chemistries, the number of IGSCC incidents has remarkably decreased [5]. The typical location of IGSCC in sensitised stainless steel piping is 3-5 mm from the fusion line, where the combination of degree of sensitisation and residual stresses are highest, Figure 10. Typical for these failures was that crack initiation was easy, resulting in initiating of several cracks (a), and that the cracks grow only in the HAZ (b), but do not generally penetrate into the weld metal. However, IGSCC can also grow outside the HAZ, as seen in cold-bend pipe (c), where the mandrel used in the bending process had caused severe surface deformation, causing transgranular initiation and early growth before intergranular crack growth deeper in the pipe wall [29, 69]. The early IGSCC cases were certainly also affected by other parameters in addition to sensitisation, e.g., welding parameters and environment, as described earlier.
In the early 90’s, cracking in Ti-stabilized stainless steel piping was detected [70-72]. Ti-stabilised stainless steels are welded using Nb-stabilised filler metal. Although the concept of stabilising stainless steels with Ti or Nb relies on formation of Ti- and Nb-carbides, tying carbon to these and thus preventing sensitisation, sensitisation can still occur very close to the fusion line, where the temperature is high enough to dissolve the carbides (i.e. >1050 °C for TiC and >1200 °C for NbC). Several of these cracks had initiated at small, sub-mm root flaws, which act both as a crevice and a stress concentrator.

Robust mitigation measures were applied in Germany to solve the problem including adoption of narrow-gap welding, change of material to Nb-stabilized stainless steel (which has a higher carbide dissolution temperature) with higher stabilization ratio requirements (minimising the material parameters affecting IGSCC), reduction of the amount of welds (minimising the amount of vulnerable positions) with sufficient amount of supports (minimising the operational stress). No IGSCC cases has been reported since these remedial actions were implemented [73].

Also in Russian RBMK’s, which operate under oxidising conditions, numerous IGSCC cases have been reported [74, 75] in the down-comer pipes. In these cases, the machining of the inner surface contributed both through the introduced deformation in the surface layer and acting as a stress concentrator. Further, the grain growth in the HAZ and high weld bead

Figure 10: IGSCC in sensitised Type 304 stainless steel HAZ (a and b) and base material (c).
thickness indicate high weld heat input, Figure 11. A high susceptibility of the joints to IGSCC was also indicated by the tendency for cracking on both sides of the weld, which has not typically been observed elsewhere, as cracking causes some stress relaxation on the opposite side of the weld. The cracking in the RBMK pipes grew in some cases to a considerable depth, at least to the “cap” of the weld (a and c). Overlay welding was at least one of the mitigation actions taken.

Figure 11: IGSCC in Ti-stabilised stainless steel in RMBK plants. The cracks grow close to the fusion line (a), in the HAZ with a clear grain growth (b). The shape of RBMK welds has a “cap” next to the outer surface of the pipe (c).

**IGSCC cases in non-sensitised stainless steel**

In the 90’s, the first cases with IGSCC in non-sensitized stainless steels were reported in BWR’s [17, 76], and later numerously in core shrouds [20]. Deformation from weld shrinkage in piping and surface grinding in the core shrouds is considered to be of major importance in these cases.

The IGSCC in the non-sensitised Type 316NG pipe was in an assembly weld at a difficult location, where assurance of lack of welding defects, e.g. lack of fusion, understandably has resulted in a choice of welding using higher than typical heat input at the root, increasing the risk (unknown at the time of welding) for IGSCC in non-sensitised SS. Also the very low sulphur content of the material required increased the required heat input. A minimum S-content was later applied, based on this lesson learned. The degree of residual strain was measured by GE, using a newly developed method, to be above 20% using EBSD, which has since been extensively used to determine the amount of residual strain in different weld joints.

The core shroud cracking was highly affected by the grinding of the surface, which was done to improve NDE quality. Also this decision was made based on the assumption, prevailing at the time of the procedure that non-sensitised SS does not suffer from IGSCC. Hardness values up to 400 HV were measured close to the surface, although crack growth occurred also into less deformed material, Figure 12. This implies, as does many other IGSCC cases that crack growth can occur in materials, in which initiation is much less likely, and focussing on increasing the crack initiation resistance is a good strategy.
Several other cases of IGSCC in non-sensitised stainless steel materials has since occurred, and the risk has been accepted to exist, and actions to mitigate this from a material’s perspective has been taken in e.g. welding procedure specifications and surface treatment practises. Recently, the role of material production and inhomogeneity of the microstructure has been accentuated. The manufacturing technologies have changed over the years, and less focus has been put on metallurgical aspects, with the result, that stainless steels with more inhomogeneous microstructures are seen in NPP components [77]. In some cases, this inhomogeneity is considered to play an important role for the observed IGSCC cases [78].

IGSCC in non-sensitised materials poses an additional challenge to a proper inspection program. In the case of sensitised stainless steels in BWR NWC environment, welds joining stainless steel pipes with high-carbon content (>0.035%) are usually classified to have a risk for sensitisation (thermal during welding or low temperature sensitisation during long-term operation) and are therefore included in the NDE programs as sites of special interest. Classification of high risk welds in non-sensitised stainless steels is not easy due to the fact that the degree of cold work is generally not known and that all affecting parameters causing increased risk are not understood or quantified. Welding with narrow-gap welding technique decreases remarkably the risk for crack initiation due to the smaller residual stresses and strains in this type of welds. However, if a crack initiates and grows within the first few grains from the fusion line, the crack path is perpendicular to the pipe axis, which also is the direction of the most likely principal stresses, from the inner to the outer surface, without any inclination of the crack path as is the case with V-groove welds [80].
Intergranular Stress Corrosion Cracking in PWR Environment

Pressurized water reactors operate at low corrosion potential and very low oxygen levels, <30 ppb. The risk for IGSCC in austenitic stainless steels in these non-oxidizing environment is, thus, much lower than in BWR NWC environment [25, 81]. Incidences with IGSCC under nominal PWR conditions have, though, been reported. Oxygen can, however, be enclosed in certain situations, such as start-ups (influenced e.g., by how the start-up is done), and lead to a risk for IGSCC in austenitic stainless steels. Although the number of IGSCC cases in PWR’s still is very low, the number seems to be increasing [82, 83]. The majority of cases have occurred in occluded locations where oxygen may be trapped after start-up and anionic impurities may concentrate. Many instances have occurred at temperatures below the primary circuit temperature, usually below 200 °C [84]. IGSCC has been observed in pressurizer heater sleeves, canopy seals in the control rod drives, steam generator safe-ends and barrel bolts etc. [84,85,86]. Also the recent cases with barrel and baffle bolt cracking, some of which have been in use quite short times, and others with a very low dose, show that IGSCC in PWR conditions, occluded and not, need still better understanding to pin-point components at risk and include these in in-service inspections [84,85,87,88]. A much smaller number of IGSCC cases have occurred under nominally free flowing conditions, all of which seem to be connected with a high amount of cold work [84,85]. The case with through-wall cracking in

Figure 12: IGSCC in non-sensitised 316NG (a), showing a high degree of residual strain (b) and in a core shroud, made from non-sensitised, low-carbon Type 304 SS [76, 79].
elbows in the residual heat system after 17 years of operation, emphasise the role of high hardness [84]. As the role of surface deformation was not fully appreciated in the beginning of PWR design, the risk for more IGSCC cases in PWR’s exist.

**Future research needs**

This paper has reviewed cases of IGSCC in the past until today, which clearly show, that as the operation of NPP’s continues, new issues arise, which require attention from plant licensees, authorities and research and development. Thus, IGSCC is still an issue for LWR’s and plant life management. A growing part of the community has understood that it is not a question of materials being immune or not immune, but a question of lower or high risk, both in BWR’s and PWR’s. The amount of IGSCC cases has decreased significantly over the years due to the remedial actions taken, but the risk is still existing. Only by identifying the most important parameters can we effectively implement risk-informed non-destructive inspection, and correctly select high-risk targets for the inspections. In the review of SCC in PWR’s [], the author concludes that “Laboratory works and results of expertises still do not enable to define relevant criteria or knowledge of the exact set of parameters which leads to SCC of stainless steels. Accordingly, the best strategy remains an inspection and repair/replacement one”.

Among the topics needing further attention are surface treatments to reach commonly accepted rules and recommendations on what can and what shall not be done to surfaces to mitigate IGSCC initiation. Improved specifications and an increased understanding of material producers on material homogeneity and appropriate requirements are also needed, based on R&D. The data and knowledge on residual stresses existing in plants is not very extensive, as is not the data on how these stresses evolve (typically decrease) during operation. Operational stresses are also of importance, especially those from start-ups and shut-downs and load following. The general understanding is, that load follow will have a negative effect on component life, but is this small, medium or high? Development of on-line monitoring techniques of stresses during plant operation would give tools for development of remedies. R&D on optimisation of pre-oxidation of new plants is very scarce, although it can have a remarkable influence on the plant life during the coming 60 – 100 years of operation.

Crack growth rate data has been produced in large numbers, and disposition lines are available. However, if we could get similar data on initiation, i.e., get a fact-based understanding on the effect of surface condition, environment, stress, dynamic loading, etc. on crack initiation, we would have better basis to implement effective remedies toward IGSCC initiation and crack growth.

IGSCC is typically, although not exclusively occurring in the HAZ or base material, and not in the weld metal (although this can occur, and has done so). However, not much is known if the risk for crack growth into the weld metal will increase due to thermal ageing of the weld metal. We know that thermal ageing affects the weld microstructure, i.e., the ferrite phase, and the cracking susceptibility of the weld metal, but we do not have much CGR data from weld metals, yet.

Mechanistic understanding needs constant improvement parallel to high-quality laboratory data production to secure safe operation of NPP’s, which is, despite political decisions in many countries, still a major method to produce CO₂-free energy. International co-operation is needed in these investigations to optimise the use of funding, knowledge transfer and avoid repetition.
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