INTERNATIONAL STANDARD

ISO
21601

First edition
2013-04-01

Corrosion of metals and alloys — Guidelines for assessing the significance of stress corrosion cracks detected in service

Corrosion des métaux et alliages — Lignes directrices pour évaluer l'importance des fissures de corrosion sous contrainte détectées en service

iTeh STANDARD PREVIEW
(standards.iteh.ai)

ISO 21601:2013
https://standards.iteh.ai/catalog/standards/sist/2080ca74-fc7d-46b2-a928-
930fc5a62055/iso-21601-2013

Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 21601 was prepared by Technical Committee ISO/TC 156, *Corrosion of metals and alloys*.

iTeh STANDARD PREVIEW
(standards.iteh.ai)

ISO 21601:2013
https://standards.iteh.ai/catalog/standards/sist/2080ca74-fc7d-46b2-a928-
930fc5a62055/iso-21601-2013

Corrosion of metals and alloys — Guidelines for assessing the significance of stress corrosion cracks detected in service

1   Scope

This International Standard provides guidelines on the appropriate steps to take when a stress corrosion crack has been detected in service and an assessment has to be made of the implications for structural integrity.

Such an evaluation should be made in the context of the perceived consequences of failure using appropriate risk-based management methodologies. Since this is application-specific, it is beyond the scope of this International Standard.

2   Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 7539-6, *Corrosion of metals and alloys — Stress corrosion testing — Part 6: Preparation and use of precracked specimens for tests under constant load or constant displacement*

ISO 7539-9, *Corrosion of metals and alloys — Stress corrosion testing — Part 9: Preparation and use of pre-cracked specimens for tests under rising load or rising displacement*

3   Principle

When a crack is detected during a scheduled inspection programme, repair will in most cases be initiated in a relatively short time-scale, by removing the component or by cutting out the damaged section and re-welding. However, in some circumstances there may be limited opportunity for repair and a pressure to keep the system in operation until the next extended outage, to minimize lost production. In other applications, it may be considered that a crack can be tolerated, provided that there is an adequate framework for predicting the evolution of the crack, defining inspection intervals, and assessing the likelihood of failure. Such an evaluation may be incorporated with an assessment of the consequences of failure into a risk-based inspection methodology. The challenges faced in living with the crack for a short or long period are establishing when the crack started, relating this to service conditions including transients (i.e. assessing whether the crack would be growing 'continuously' or only in response to specific fluctuations in service conditions), evaluating the mechanical driving force, characterizing the state of material through which the crack initiated and will propagate, assessing the laboratory database and translating this to the perceived service operation conditions using fracture mechanics or other concepts.

Leak before break (LBB) may also need to be evaluated where there is the risk of explosive or catastrophic failure, but, in practice, stress corrosion is usually detected and repaired for operational reliability reasons.

The purpose of this International Standard is to provide guidance in developing a damage-assessment process with some guidance on measures to control growth rates.

4 Characterization of the nature and origin of the crack

A first step is to develop a complete physical assessment of the crack[1] in terms of identifying its shape and dimensions (uncertainty in defect size assessment should be noted) as this will feed into any finite element/fracture mechanics analysis. This should include an assessment of the crack location in relation to local stress concentrators, welds, crevices (e.g. at fasteners, flanges), and also the details of the crack path. If more than one crack is present, the crack density and the spacing between the cracks should be noted in view of possible future coalescence. Also, the state of the surface should be assessed for general or pitting corrosion damage.

Characterizing the crack as a stress corrosion crack may be possible from visible observation, e.g. significant crack branching (although extensive branching, albeit possibly beneficial, may preclude simple stress analysis and warrant removal of the crack). In most cases it is deduced from prior experience and awareness of the likelihood of other failure modes but recognizing that loading in service does not usually correspond to the simple static load tests conducted in the laboratory. Thus, there may be cyclic loading to some degree or dynamic straining associated with transient temperature changes. In many cases, distinction between a stress corrosion failure mechanism and a hydrogen embrittlement mechanism may not be possible. Where crack extension and remanent life assessment are the primary concerns, this may not be a critical issue provided that the laboratory data used for assessment relate to the particular service conditions. However, mitigation procedures can be contingent upon knowledge of the cracking mechanism.

Attention should be given to the operational history to assess the extent, if any, of system upsets that may have contributed to the onset of cracking.

5 Definition of service conditions and system history

5.1 Stresses

5.1.1 Operational stresses

Operational stresses are usually well known from the design process and, in practice, rarely critical except in the sense of being additive to residual fabrication stresses. However, a word of caution is needed. These are sometimes higher than they were designed to be due to discrepancies between the design drawings and the as-manufactured components as a consequence of inadequate control during manufacture. This can result in higher stresses than intended by designers where changes in section occur. For instance, the low pressure (LP) turbine shaft failures at Ferrybridge (1975)[1] occurred because the radius of the centre-collar stress relief grooves was smaller than the design value as a result of poor machining.

Other problems can arise if machining score marks are not ground out, causing increased stresses locally and sites for localized corrosion.

5.1.2 Residual stresses

Residual stress characterization *in situ* in service may be undertaken by a variety of methods. X-ray diffraction (XRD) is most commonly used. However, since the depth of material sampled is less than 10 μm, rough surfaces can give misleading results. *In situ* neutron diffraction methods may be possible with some relatively portable components but it is expensive. Depth variation of residual stress can be obtained by incremental hole-drilling but this is destructive, albeit at a local level, and requires repair. There is more scope for evaluation of removable parts and here XRD and electrochemical polishing can also be used for depth profiling of residual stress. Non-destructive depth profiling of residual stress requires access to a synchrotron radiation source and by implication is limited to removable parts. In the

---

1) Detection of the crack in the first instance may have been by a range of methods including ultrasonic testing, acoustic emission, visual inspection, dye penetration, electromagnetic and potential drop methods. More detailed information on crack shape and size may be derived from X-ray tomography, though confined to removable parts and potentially size limited.

absence of measurement, the residual stress may be assumed to be at the effective yield strength (taking into account multi-axial stress state) for the parent material or weld metal, as appropriate, according to the location. However, the yield stress needs to be carefully evaluated in the light of the work-hardening capacity of the material and likely extent of local deformation. For critical applications, mock-ups may be necessary for the evaluation of residual stresses and cold work by X-ray diffraction. Post-weld heat treatment should relieve residual stress but it may not always be performed fully or adequately. Hydrotesting of pipes or vessels may also relieve the residual stress, by an amount proportional to the applied pressure stress (e.g. Hewerdine et al.[2]). Since stress corrosion crack growth rates are often stress intensity factor (K) independent or weakly dependent on K in the Stage II region (see Clause 7) there may be some latitude in characterizing the residual stress for analysis above K_{ISCC} (KISCC: Mode I threshold stress intensity factor for stress corrosion cracking) but recognizing that there will be uncertainty in calculating the critical flaw size for unstable fracture.

5.1.3 Multi-axial stresses

Multi-axial stresses are usually dealt with by determining the maximum principal tensile stress direction and assuming that stress corrosion cracks grow perpendicular to that direction. In fact, this is certainly an oversimplification and remains an area requiring further study. Isolated studies have shown that the biaxial or triaxial stress state should not be ignored.

5.1.4 Transients (e.g. thermal transients)

The usual concern with thermal transients is that they superimpose a cyclic load on the static stresses, which may enhance the risk of cracking as described later. In addition, larger thermal transients typically associated with start-up or shut-down of a plant will introduce significant dynamic loading for significant periods which again can enhance the risk of cracking (see later).

5.1.5 Corrosion product wedging

Since the oxidized forms of common structural metals occupy a significantly larger volume than the metal from which they came, possible additional loading due to wedging cannot be ignored in crevices or growing cracks. In practice, only a few circumstances are known where this is practically important and usually arises where there is a significant occurrence of crevice corrosion.

5.2 Service environment

5.2.1 General

Intended service environments are normally well characterized (temperature, water chemistry, partial pressure of gases, total pressure) but lack of operator objectivity as to possible environmental transients is a serious handicap in many service failure investigations.

5.2.2 Excursions from normal operating conditions

The probability of a leaking condenser, ion-exchange failure, residue from chemical cleaning, cooling water failure (giving temperature rise), oxygen ingress etc. all require objective assessment and wishful thinking on the part of plant operators in this respect is a serious handicap to finding practical solutions. The operational history should be examined carefully to assess the extent to which excursions occurred.

The concern with a transient increase in temperature or change in service environment is that it may move the system into a domain for activation of stress corrosion cracking (SCC), which would otherwise not be a concern. Thus, in assessing the significance of a crack, the exposure history should be examined and the extent of available data for predicting the likelihood of growth and the growth rate at the normal temperature or chemistry following an excursion evaluated. Often, the data are limited.

5.2.3 Solution concentration processes — development of local environments (crevice formation, hideout/evaporation, deposits)

Attention should be given to the existence of crevices that may induce local changes in solution chemistry and lead to corrosion. These may be the precursors of cracks and need to be considered when assessing laboratory data or undertaking testing in simulated service environments. Concentration processes due to hideout/evaporation under heat transfer conditions can be much more powerful than those due to ion migration. The theoretical limit of concentration can be estimated from the solubility of impurity solutes at the operating temperature and the local superheat available. A solute will concentrate until it raises the boiling point, until boiling no longer occurs given the local superheat and system pressure, or until it reaches its solubility limit if that intervenes beforehand. In the last case, a thin, very concentrated, liquid layer will form, commonly covered in a blanket of steam (which may not necessarily be better from a stress corrosion viewpoint).

5.2.4 Corrosion monitoring

Corrosion monitoring can be an important tool in assessing the aggressiveness of the service environment and is particularly useful when operational conditions fluctuate due to transients in water chemistry or contamination. If these transients can be identified as the occasions when stress corrosion cracks might develop and propagate, then a more informed basis for prediction may be generated, based on the number of damaging cycles, rather than simply the elapsed time of exposure. This may also allow benchmarking of the onset of initial damage, from the first transient or when a coating or other protective system has failed.

6 Material characteristics

NOTE   The first step is to ensure that the material of relevance actually corresponds to that specified at the design stage. There are a number of factors that may subsequently affect the performance of the material.

6.1 Cold work

Cold work in a material can be introduced during fabrication or in response to surface machining/grinding. In much laboratory testing, specimens are usually wet-ground to a well-controlled surface finish, typically with an *Ra* value less than 1 μm, the primary purpose being to ensure repeatability of data and avoid any influence of surface cold work. In service, materials are often ground fairly crudely (or indeed may be supplied with retained cold work from processing). Poorly controlled (abusive) machining can cause surface overheating. Correspondingly, there may be significant surface stresses, deformation layers, increased hardness, and the possibility of microstructural transformation (e.g. bainite to untempered martensite) if the alloy is metastable or metastability is induced by the thermal history. High dislocation densities and associated short-circuit diffusion pathways can enhance some types of stress corrosion. For this reason, cracking in service may not be reliably predicted from laboratory tests without attention to these details.

The uncertainty in prediction is the extent to which cracks initiated in this layer (with gradient in residual stress and deformation) will continue to propagate once they have grown beyond the cold-worked region. There are situations in service where non-propagating cracks have been observed but there are also indications that if the depth of cold work is sufficient the cracks will continue to propagate. A key aspect will be the residual stress gradient. If this falls off steeply from the surface a crack may initiate but then cease to propagate because the combination of stress and crack size is not sufficient to attain the critical value of the stress intensity factor for sustained propagation (see 7.1). If the stress gradient is more gradual then sustained propagation may ensue. The problem is that characterization of the degree and depth of cold work *in situ* may not be straightforward but may be inferred from experience with the material preparation route.

6.2 Welding

Assuming that radiographic assessment has ensured that there were no physical flaws of significance, the issue for welded sections as far as *propagation* of cracks is concerned is primarily in relation to

residual stress, hardness, and local microstructural and/or microchemical changes, although joint geometry could have an influence on the mechanical driving force and local environment chemistry.

The concern for welds in relation to the microstructural and microchemical aspects and their impact on stress corrosion cracking is the possible departure from the weld procedure qualification, with perhaps too high a heat input and inadequate filler leading to sensitization at grain boundaries or at precipitate particles, elongated and clustered inclusions and local hard spots. Measuring these characteristics *in situ* is a challenge. In principle, electrochemical potentiodynamic reactivation (EPR) can detect sensitization depending on accessibility. Metallography is feasible for removable parts and similarly eddy current and Barkhausen noise can detect hard spots but both require surface polishing and are most applicable to removable parts.

6.3 Ageing

6.3.1 Thermal ageing

Materials operated at high temperature for extended periods can undergo thermal ageing induced microstructural and microchemical changes that often increase stress corrosion susceptibility. Common examples include cast stainless steels undergoing spinodal decomposition of the ferrite with very significant hardening and ageing of precipitation-hardened stainless steels such as 17-4PH. Once hardness values exceed 350 HV, experience shows that the risk of environmentally induced cracking in aqueous environments increases and above 400 HV cracking failures are practically guaranteed. Another problem is thermally induced sensitization of austenitic stainless steels (particularly if the C-content exceeds 0,03 % and they are not stabilized by Nb or Ti) due to the precipitation of chromium carbides at the grain boundaries on prolonged service at (or slow cooling through) temperatures in the range 425 °C (or less for low-temperature sensitization) to 875 °C.

Also, microstructural changes, e.g. in high pressure/intermediate pressure turbine components, can lead to a deterioration in toughness and hence in the critical flaw size for unstable fracture.

6.3.2 Irradiation damage

Irradiation damage, insofar as it may lead to significant hardening, may have a similar effect to the thermal ageing described above. Another effect observed in austenitic stainless steels subject to high neutron irradiation doses exceeding about one displacement per atom is a significant change in grain boundary composition due to the migration of point defects to sinks such as grain boundaries (as well as dislocations and free surfaces). The most notable consequence in common austenitic stainless steels is a reduction in the chromium concentration in a very narrow band about 10 nm wide at grain boundaries leading to intergranular stress corrosion cracking (ISCC) in oxidizing high-temperature water. It is sometimes called irradiation-induced sensitization but there are no grain boundary carbides as with thermally induced sensitization.

6.4 Microstructural orientation

The orientation of the microstructure relative to the principal stresses can influence the evolution of stress corrosion cracking. This is a particular issue where there is an elongated grain structure and significant differences in properties between the longitudinal and transverse directions as observed, for example, in aluminium alloys.

7 Prediction of K_{ISCC} and crack growth rates

NOTE   The complexity of service conditions and the corresponding uncertainty in crack growth kinetics necessitates a very conservative approach to crack-tolerant philosophies. If the consequences are perceived to be non-critical, in many cases the most relevant crack growth data may be derived from further monitoring of the detected crack. This has the virtue also of benchmarking laboratory predictions. The most commonly used approach is to characterize the K_{ISCC} value for the material and to make judgements as to whether the crack is beyond the limit for this threshold.

7.1 K_{ISCC}

Clearly, if the detected crack is perceived to be a stress corrosion crack then a threshold has been exceeded. However, that may be a threshold for initiation from a plain surface, corrosion pit or shallow defect for which linear elastic fracture mechanics (LEFM) is not applicable (Figure 1). In these cases, K_{ISCC} might be better perceived as a threshold for subsequent sustained crack growth (or for crack arrest).
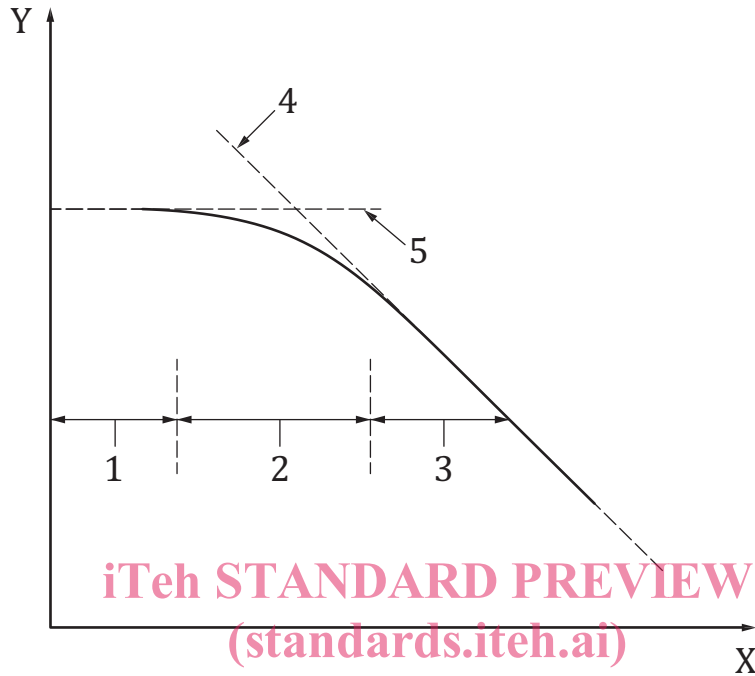

Key

Y   Stress (log)

X   Flaw depth (log)

1   Initiation of stress corrosion cracking

2   Shallow cracks

3   Deep cracks

4    $K = K_{ISCC}$

5   Stress = σ_{SCC}

Figure 1 — Schematic diagram of the two-parameter approach to stress corrosion cracking

The concept of K_{ISCC} is not trivial and the value is sensitive to the environmental conditions, temperature and loading characteristics. Accordingly, data obtained for one condition should not be transposed to another.

However, K_{ISCC} should not be regarded as an intrinsic characteristic of the material as it will depend sensitively on the environment and loading conditions, which should reflect those for the service application. Also, there may be long-term changes in the material due to exposure that are not reflected in short-term laboratory tests. The definition implies no sustained crack growth, or crack arrest, below this value, which intrinsically brings in issues of resolution of the crack size measuring method and the patience of the experimenter.

For long cracks, the behaviour is typically as represented in [Figure 2], where typical behaviour for a fatigue crack is shown for comparison.
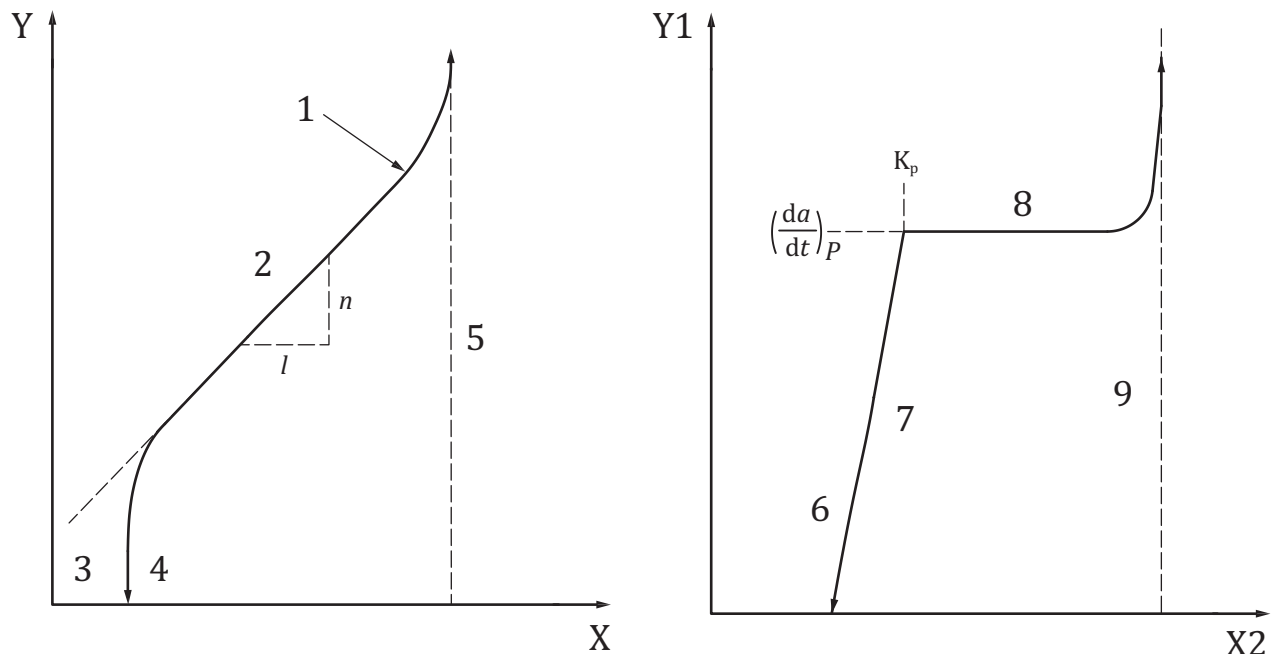
a) **Fatigue crack growth**   b) **Stress corrosion crack growth**

Key

Y	Log ($\mathrm{d}a/\mathrm{d}N$)	Y1	Log ($\mathrm{d}a/\mathrm{d}t$)
X	Log (ΔK)	X2	Log (K)
1	Terminal region (C)	6	$K = K_{\mathrm{ISCC}}$
2	Intermediate region (B)	7	Stage I
3	$\Delta K = \Delta K_{\mathrm{th}}$	8	Stage II (Plateau, p)
4	Initial region (A)	9	$K = K_{\mathrm{Ic}}$
5	$K_{\mathrm{max}} = K_{\mathrm{Ic}}$		

Figure 2 — Schematic illustration of typical crack growth behaviour in a) fatigue and b) stress corrosion cracking[3]

It is common to conduct K_{ISCC} tests under static load conditions and accordingly results unrepresentative of service are often obtained. Structures are seldom subjected to purely static loading and it is well known that the value of K_{ISCC} can be considerably reduced if a dynamic loading component is involved; for example a thermal transient, following an outage, or superimposed cyclic loading, even of small magnitude.

Should it be decided that K_{ISCC} values obtained under static loading are appropriate, these can be determined using the procedures described in ISO 7539-6. This International Standard describes both crack initiation and crack arrest methods using fatigue pre-cracked, fracture mechanics type specimens tested under constant load or constant displacement. For some systems, the value may vary depending on the method of measurement, e.g. increasing K or decreasing K experiments. As a fatigue pre-crack is somewhat artificial and may affect the transition to a stress corrosion crack, a decreasing K, crack arrest, type of experiment may be more pertinent.