ESA APPROACH TO THE PREVENTION OF STRESS-CORROSION CRACKING IN SPACECRAFT HARDWARE

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Abstract

The present work addresses the importance of stress-corrosion cracking (SCC) as an insidious failure phenomenon which affects the integrity and safety of spacecraft hardware. SCC requirements are particularly important when selecting metallic materials for payloads, these being subjected to long term storage before flight. The ESA general approach to the determination of SCC susceptibility and selection of materials is presented with reference to the ECSS applicable standards. Test methodology, classification and qualification of materials are discussed in the light of the requirements for the prevention of SCC in spacecraft hardware.

1. Introduction

Stress-corrosion cracking (SCC) is a failure phenomenon which occurs in engineering materials, typically metals but also ceramics and polymers, by slow environmentally induced crack propagation. The crack propagation is the result of the combined synergetic interaction of mechanical stress and corrosion [1]. Figure 1 shows an example of SCC revealed during the metallographic analysis carried out on the aluminium alloy 7449-T651 sample tested for SCC susceptibility [2]. SCC of aluminium alloys is often intergranular, Figure 2. In these alloys, according to the electrochemical theory, the localised decomposition of solid solution along the grain boundaries makes them anodic to the surrounding regions promoting intergranular stress-corrosion cracking.

SCC occurs in the presence of a corrosive environment, typically aqueous, and under sustained tensile stresses. Water condensation, either atmospheric or in inhabited modules, exposure to coastal environment, typically at launch sites, and the presence of chemical substances such as cleaning fluids or accidentally released substances (e.g. hydrazine, cleaning solvents and hydraulic fluids) can promote stress-corrosion cracking. Exposure to these environments may occur during storage, transportation, these being particularly important for payloads, and during service. In the past a relevant number of structural failures occurring at launch sites were caused by SCC. It was found that these failures could have been prevented by selecting materials highly resistant to SCC. A review of the contribution of SCC to failures at launch sites can be found in Ref. [3].

2. Prevention of SCC

Tensile stresses in a component are the result of externally applied loads experienced during storage, transportation and service, and residual stresses introduced during manufacture and assembly. Whereas tensile stresses associated with external loads can be determined during design with a certain degree of confidence, tensile residual stresses introduced during manufacture and assembly are more difficult to predict and therefore often underestimated or neglected (residual stresses can often approach the material yield strength in weldments and bolted joints, [4]). These residual stresses are generally sustained stresses. For this reason they can promote SCC and should always be considered when assessing the risk of failure by stress-corrosion cracking of a component.

Manufacturing and detail design can reduce the risk of SCC failures by reducing tensile stresses acting in the short-transverse direction of the material and reducing assembly stresses resulting from mismatch or excessive clearance between elements in mechanical joints. Figure 3 shows a typical example where sustained stresses are introduced into the component during assembly. The excessive clearance between lugs results in normal stresses parallel to the short transverse direction in the material. In this case, SCC can be prevented by modifying the manufacturing process - to change the grain orientation with respect to the direction of sustained tensile stress - and the design - to reduce the clearance between lugs. An alloy/heat treatment highly resistant to SCC should be selected for this application.

SCC is influenced by several factors such as stress level, type of corrosive environment, temperature, alloy chemical composition, temper, grain structure and mechanical properties [1]. Deformations such as buckling and twisting of material in the vicinity of weldments often indicate the presence of high residual stresses. These may approach the yield strength of the alloy and unless suitably relieved by means of stretching and/or heat treatment, such stresses can promote failures by SCC. Surface protection treatments against corrosion such as chemical conversion coating are not particularly effective in the prevention of SCC. The effect of chemical conversion coating on SCC was assessed in Ref. [5]. Samples of the SCC susceptible 7010-T7451 aluminium alloy were chemical conversion coated and tested for SCC together with unprotected samples of the same alloy using the constant load test method. Metallographic analysis showed evidence of SCC in both bare and chemical conversion protected samples.

SCC is a time dependant phenomenon. Time-to-failure in a SCC susceptible alloy subjected to constant tensile stress decreases rapidly with increasing stress level. A threshold stress value is defined as the maximum stress that the material can sustain in a particular environment without SCC failure to occur. In design of spacecraft hardware, this definition is often of no practical applicability. Since the prediction of in-service SCC failure is difficult and the possibility for inspection and repair remote, the current approach is based on a safe-life philosophy by which only stress-corrosion resistant alloys are selected for spacecraft structural applications. In this light, the determination of SCC susceptibility and an appropriate selection of materials, in the preliminary stages of design, is of paramount importance for the prevention of SCC failures in spacecraft.

3. Determination of stress-corrosion cracking susceptibility of materials

It is common practice to determine resistance to SCC by loading smooth specimens at constant stress level for a fixed period of time. The majority of experimental data published in literature refers to a 30-day exposure test under constant load to achieve 75 % of the yield strength of the parent material. This test method has been used in Europe for more than 30 years [6], and is described in the ESA specification ECSS-Q-70-37 which is the standard method for determining the susceptibility of metals to SCC used by the European space industry. This test method (prior to 1998 it was known as ESA standard PSS-01-737) has generated a very large database of results. It is also applied to weldments and as a quality control during production.

The method involves the exposure by alternate immersion to 3.5 % NaCl water solution of specimens stressed in the direction transverse to grain orientation for which the SCC resistance is least. Unstressed control specimens are exposed to the same environment to provide a basis for comparison. Figure 4 shows the testing procedure. The susceptibility is assessed by tensile tests to compare the residual strength of the specimens exposed stressed and unstressed, and by metallographic examination of microsections from stressed and control specimens. Metallographic examination allows the investigator to distinguish failures caused by severe corrosion which would occur independently of stress, from those caused by SCC. For this reason, the ESA test method prescribes that metallographic analysis is carried out to compare surface damage of stressed specimens with that of control (unstressed) specimens.

Prior to stress-corrosion testing, the 0.2 % proof stress, ultimate stress and elongation are obtained from similar specimens. These values are used to establish the SCC test stress level (calculated as 75 % of the 0.2 % proof stress of the material) and provide reference for comparison with specimens to be tensile tested after surviving 30 days in the stress-corrosion test. The SCC tests are carried out in triplicate, the specimens being loaded in tension by calibrated springs or hydraulic loading devices. Tested alloys are classified as Class 1, 2 or 3 materials depending on their high, moderate or poor resistance to SCC. The assessment of test results and the material classification criteria are detailed in ECSS-Q-70-37. Multiple batch testing, in-service experience and literature data are finally used to grade alloys as Table I, II or III, respectively, in the official classification.

The ESA constant-load test overcomes the reproducibility problems associated with constant-strain stress-corrosion tests, which suffer due to relaxation of the stressing jigs; or after the onset of SCC in small specimens, there is a reduction in specimen stiffness, plastic strain and creep with an attendant reduction in the initial stress level [3]. This obviously leads to an underestimate in the level of susceptibility to SCC of tested materials.

The constant load test as detailed in ECSS-Q-70-37 often mimics the loading experienced by spacecraft structures prior to launch. For instance, an aluminium bracket that supports a propellant tank filled with hydrazine will be exposed to a constant load. Alternatively, a torque bolt might be considered to be loaded by constant strain. In both cases the launch-site, whether at Kourou or Kennedy, can be considered to be corrosive due to a saline environment caused by various Trade Winds throughout each year [3].

Damage during exposure is generally the result of two factors: damage caused by SCC and metal corrosion typically in the form of surface pitting or in other forms. Experimental evidence has shown that although some alloys are not SCC sensitive they exhibit poor corrosion resistance. This is the case of the MIG welded 7020-T6 aluminium alloy which has been post-weld solution heat treated and precipitation hardened. This alloy was tested using the constant load method [7]. Although metallographic analysis indicated no evidence of SCC in the stressed specimens, Figure 5, both stressed and control specimens showed the same the damage extent regardless of the presence of sustained tensile stresses in the former ones. It could be concluded that the weldments exhibited good resistance to SCC and that the damage was essentially caused by pitting corrosion in the transition region between the fused metal and parent plate.

It is important to notice that the alternate exposure to 3.5 % NaCl water solution provides a means of accelerating the SCC phenomenon. This exposure method is not necessarily representative of a specific corrosive environment, i.e. exposure to salt water or sea coastal environment. In fact, the implicit assumption of this method is that an alternate exposure to 3.5 % NaCl water for 30 days is representative in terms of SCC damage of a long-term exposure in a generic corrosive environment. This is the fundamental engineering assumption of the testing method and its validity and significance should always be discussed in the light of the specific in-service exposure conditions.

4. Stress-corrosion cracking requirements for spacecraft hardware

ECSS-Q-70-36 details the quality assurance and materials requirements that are necessary for the avoidance of SCC. Company designers should select materials for structural applications from those heat treated alloys that are known to possess a high resistance to SCC. In the first instance they are encouraged to consult ECSS-Q-70-36 and select alloys from the Table I. Alternatively designers will be obliged to demonstrate by testing and experience that the proposed material is highly resistant to SCC. This practice is essential to guarantee integrity and safety of spacecraft hardware.

Materials possessing high resistance to SCC and qualified for structural applications are listed in Table I of ECSS-Q-70-36. Heat treated alloys which exhibit moderate and low resistance to SCC are listed in Table II and Table III, respectively, of the same standard. Since different SCC test methods and test conditions produce results that are not necessarily comparable [8, 9], all alloys listed in Table I, II and III of ECSS-Q-70-36 were evaluated using the ESA constant-load test method with a stress level of 75 % of the 0.2 % proof stress. This guarantees homogeneity and comparability of test results.

Table II materials, which are moderately resistant to SCC, are used only in cases where a suitable alloy cannot be found in Table I. In order to prevent occurrence of in-service SCC failures, the suitability for use of a Table II material is assessed on a case-by-case basis. The designer is formally asked to provide justification for the selection of a Table II material. The evaluation is carried out considering the estimate of any sustained tensile stress and its orientation with respect to the short-transverse direction in the material, the environment to which the component will be exposed, the fabrication processes and any finishes applied for corrosion protection. The effect of failure by SCC of the component on the overall integrity and function of the major assembly or mission is assessed. Safety considerations are of primary importance particularly for hardware of manned spacecraft.

Table III materials being highly susceptible to SCC are considered for use in non-structural applications or in applications where it can be demonstrated conclusively that the probability of SCC failure is remote because of low sustained tensile stress, suitable protective measures or an innocuous environment. The evaluation procedure is similar to that carried out to assess Table II materials.

Special applications may require the use of heat treated alloys which are not listed in ECSS-Q-70-36, or may involve exposure to specific environments i.e. chemical substances or other. The suitability of these materials is assessed by either means of tests conducted in an environment representative of the specific application or by means of direct comparison with similar heat treated alloys for which SCC susceptibility is known to be low.

5. Conclusions

1) Stress-corrosion cracking failures can be prevented by an appropriate selection of materials, manufacturing processes and design solutions aimed to reduce tensile stresses in the short-transverse direction of the material.

2) The ESA constant-load test method to determine SCC susceptibility of materials has been used in Europe for more than 30 years and it is the standard method used by the European space industry.

3) The test method involves a 30-day period of alternate exposure at 75 % of 0.2 % proof stress and allows by metallographic analysis the distinguishing between SCC and simple corrosion.

4) Heat treated alloys are classified in three tables with respect to the their level of susceptibility. Classification is based on the results of the SCC tests, previous in-service experience and literature data. Unclassified heat treated alloys are assessed for SCC on a case-by-case basis.

5. References

1. Jones, R.H. and Ricker, R.E, *Mechanisms of stress-corrosion cracking, Stress-corrosion cracking: materials performance end evaluation*, ASTM Int, 1993, pp. 1-40
2. ESA/ESTEC Metallurgical Report 2662, *Stress corrosion testing of aluminium alloys 7349-T6511*, 7449-T7951, 7449-T651 and 7040-T7651, June 2000
3. Dunn, B.D, *Metallurgical assessment of spacecraft parts, materials and processes*, Praxis publishing, Chichester, UK, 1997
4. Hill, H. N, *Residual welding stresses in aluminum alloys, Metal Progress,* August 1961, pp. 92-96
5. ESA/ESTEC Metallurgical Report 2699, *Stress corrosion testing of AA 7010-T7451 with chemical conversion coating and anodising protections,* September 2000
6. Nema, P, *A reference method for determining the stress corrosion susceptibility of aluminium alloys under constant load in laboratory tests*, Com. from Alusuisse, Research Centre Neuhausen, 1974, pp. 655-661
7. ESA/ESTEC Metallurgical Report 2454, *Stress corrosion testing of MIG welded AA 7020-T6 after post-weld solution heat treating and precipitation hardening*, March 1998
8. Sprowls, D.O, *Evaluation of stress-corrosion cracking*, ASTM Int, 1993, pp. 363-415
9. Parkins, R.N, *Development of strain-rate testing and its implications*, ASTM STP 665, 1979, pp. 5-25

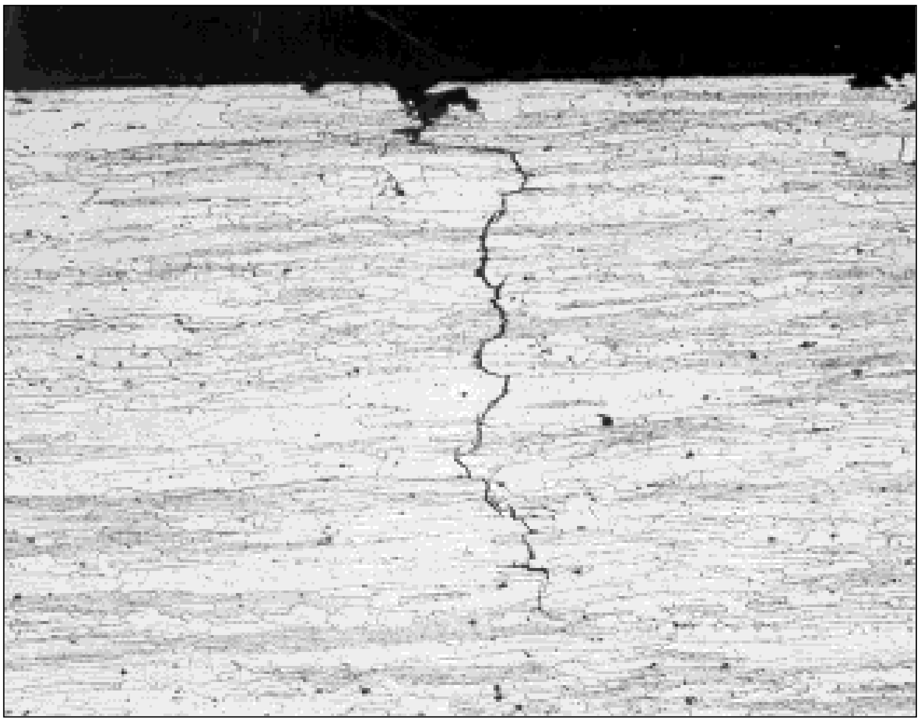

Figure 1 Transcrystalline stress-corrosion cracking revealed by metallographic analysis carried out on a 7449-T651 aluminium alloy sample tested for SCC susceptibility. The crack initiated from a corrosion pit formed during exposure to 3.5 % NaCl water solution (Mag. X100).

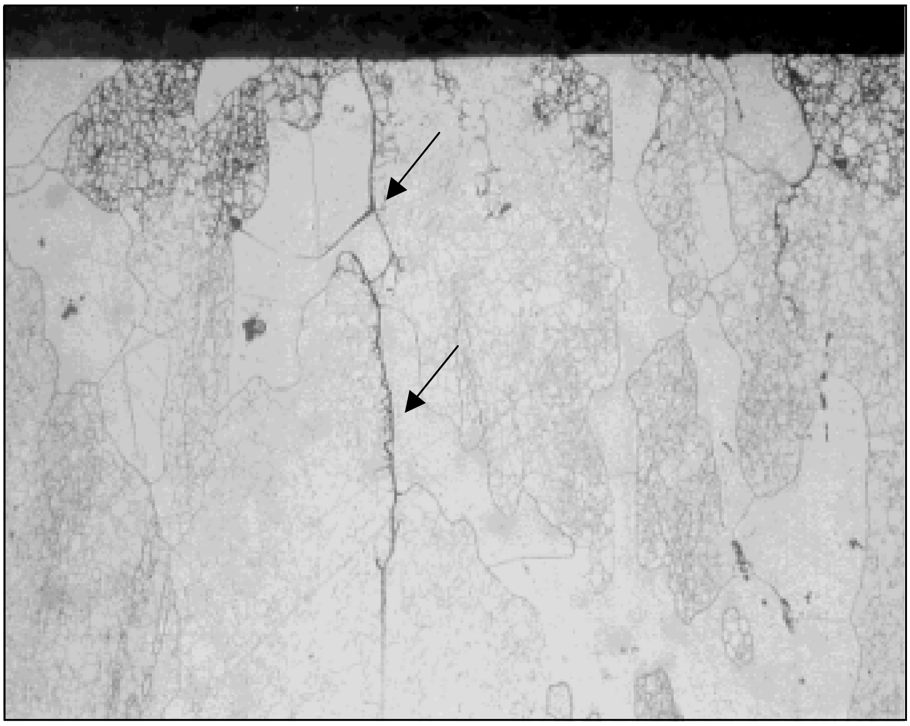

Figure 2 Example of intergranular stress-corrosion cracking in a 7075-T651 aluminium alloy tested in accordance with the constant load method ECSS-Q-70-37 (Mag. X200).

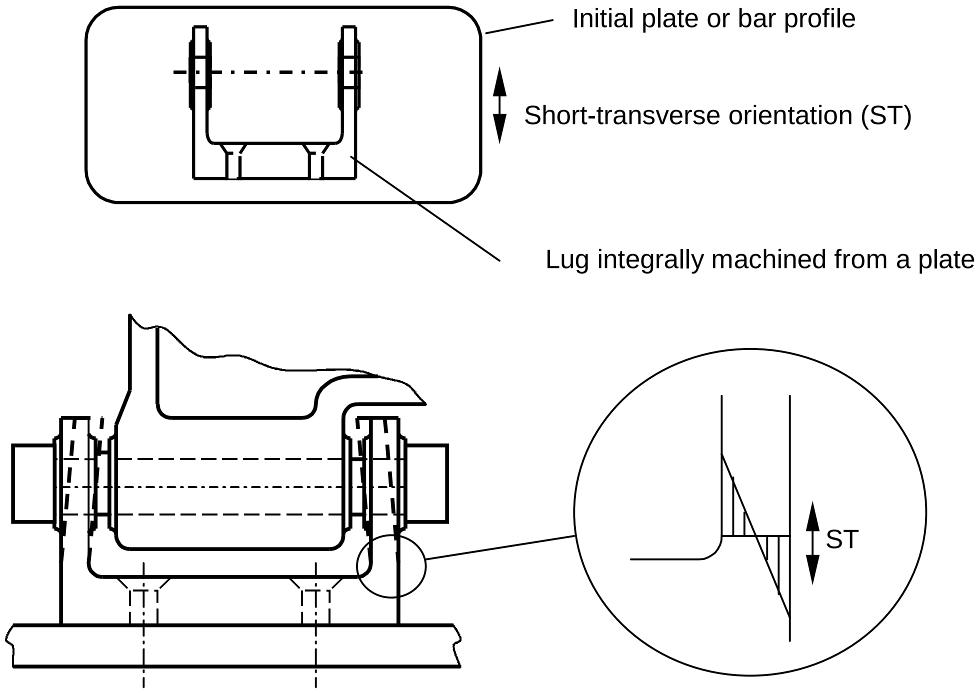

Figure 3 A typical case where sustained stresses are introduced into the component during assembly. SCC can be prevented by modifying the manufacturing process - to change the grain orientation with respect to the direction of sustained tensile stress - and the design - to reduce the clearance between lugs. An alloy/heat treatment highly resistant to SCC should be selected for this application.

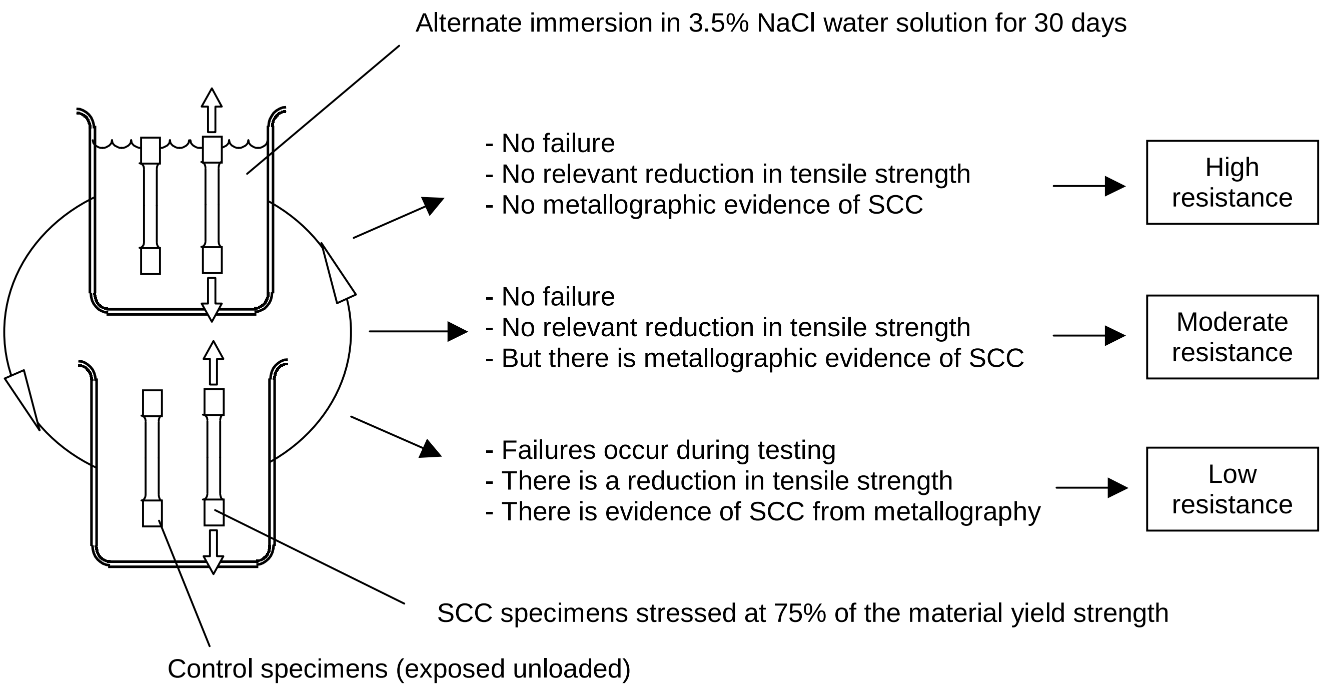

Figure 4 Representation of the constant load SCC test procedure and interpretation of results.

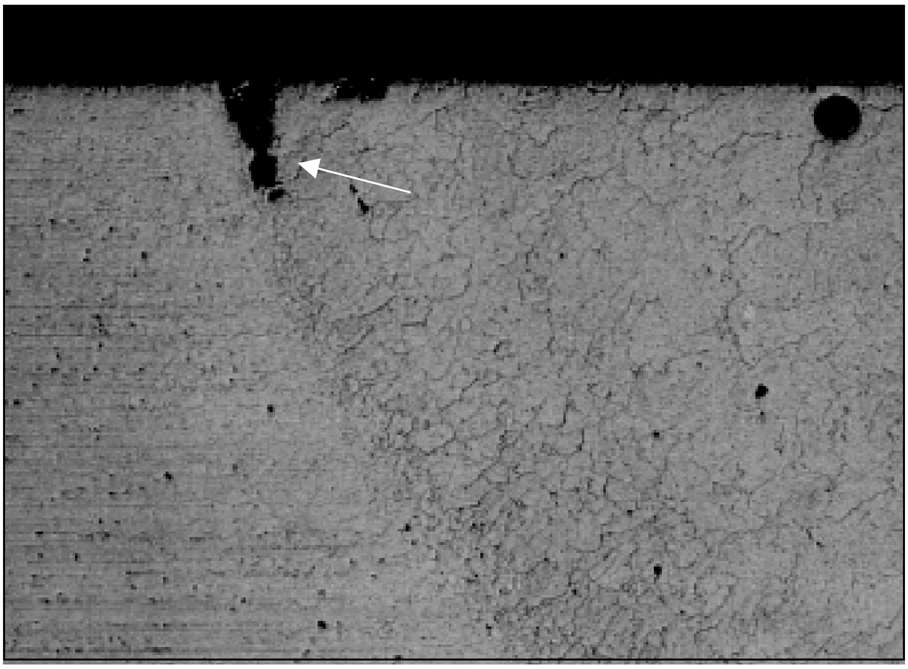

Figure 5 Example of pitting corrosion damage in a MIG welded 7020-T6 aluminium alloy tested for stress-corrosion cracking. A corrosion pit, visible in the photo, in the region of transition between the fused zone and the parent plate. No evidence of SCC was found (Mag. X50).