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IGSCC IN A BWR STEAM LINE AFTER 30 YEARS OF OPERATION

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ABSTRACT

Intergranular stress corrosion cracking was observed in a 406 x 8 mm stainless steel BWR steam pipe line after 30 years of operation. The material is Type 304 with a carbon content of 0.04%. The operating temperature is 170°C. The failure analysis showed that the material was sensitized, and that the cracking had occurred at a location where re-welding due to weld defect removal had been performed during the assembly of the pipe. The crack located at a distance of about 8 – 11 mm from the fusion line. The degree of sensitization, measured next to cracked region, showed clear sensitization, with a maximum I_r/I_a – value of 2.32%. Although IGSCC in sensitized stainless steel is a well-known phenomenon, this failure has characteristics worthwhile reporting, i.e., the failure occurred at a temperature, where low temperature sensitization is not effective, and the crack locates at a higher than typical distance from the fusion line, which is at least partly due to the thinner wall thickness compared to typical primary piping. Factors affecting crack initiation include at least the relatively few transients during especially start-up of the plant after annual outages, showing that although steady plant operation with few transients obviously are beneficial as reducing the risk for events, crack initiation can occur with time in components fulfilling the requirements for SCC, i.e. a susceptible material, an oxidizing environment and a high stress.

Keywords: stainless steel, Type 304, failure, IGSCC, BWR

1. INTRODUCTION

Intergranular stress corrosion cracking (IGSCC) in sensitized austenitic stainless steels was earlier frequently observed in BWRs [1]. The majority of IGSCC cases reported are in sensitized Type 304 stainless steels, and only a few in low carbon Type 304 or 316 stainless steels. The susceptibility of austenitic stainless steels to IGSCC initiation and crack growth is highly dependent on grain boundary composition, oxidizing power of the environment and stress [2]. Chromium depletion of the grain boundaries due to nucleation and growth of chromium rich carbides is known to increase the susceptibility to IGSCC [3]. Measures to avoid this grain boundary chromium depletion are to decrease the amount of free carbon in the material by e.g. reducing the overall carbon content, thus suppressing the carbide formation. Nowadays, a maximum carbon content of 0.035% is widely applied for specifications of Type 304 and 316 stainless steels, while higher carbon contents were allowed earlier. Carbon can also be bound in other types of carbides, as is done in Ti- and Nb-stabilized stainless steels. However, IGSCC has also been observed in stabilized stainless steels, and then more in Ti-stabilized than in Nb-stabilized stainless steels [4]. From the beginning of this century, reports on IGSCC in non-sensitized low carbon stainless steels started to appear [5]. In these cases, the amount of deformation is one parameter affecting the cracking susceptibility and the crack growth rate [6]. Further remedies to avoid IGSCC have been to adapt more stringent water chemistry or apply non-oxidizing water chemistry (Noble Chem^R or hydrogen water chemistry), and to apply improved welding parameters to reduce the residual stresses.

The two Finnish BWRs, operating on NWC, suffered also from numerous IGSCC cases in the 80's. These observations resulted in large replacement programs, where Type 316LN stainless steel was mainly used for the replacement. All main primary pipes with a carbon content exceeding 0.035% were identified to ascertain that these pipes were within the replacement program. Also research programs were launched to achieve a better understanding of affecting parameters, including low temperature sensitization (LTS) [7]. Since then, the continuous modernization strategy of the plant has proceeded, including also

replacements of stainless steel piping, and only a few IGSCC cases have occurred since the early days of operation. The IGSCC cases in the 80's occurred mainly in primary piping made from Type 304 stainless steel. Recently, a leak was observed in a steam line made from Type 304 stainless steel, operating at lower temperature and in a steam-water mixture environment. This event is reported and discussed in the following.

2. BACKGROUND

A leak was observed in the steam line of a BWR-plant during a walk-down inspection. The leak was temporarily repaired using a patch. The final repair, i.e., replacement of the weld with the leak, was performed during the next outage. The steam pipe line in question was originally made of carbon steel, but was replaced due to observed erosion with SS2333, similar to Type 304, stainless steel about 30 years before the leak. The pipe dimensions are 406 x 8 mm, and the operating conditions are steam-water mixture with a temperature of 170°C and a pressure of 8 bar. The weld with the leak was an assembly TIG-weld, which had to be re-welded two times due to observed flaws in the weld during the assembly.

The about 30 x 10 mm large section removed for failure analysis was decontaminated using sand blasting before investigations.

3. PERFORMED INVESTIGATIONS

A failure analysis was performed to reveal the reason for the leak. This included visual inspection, microstructural characterization, fractography using scanning electron microscopy (SEM), chemical analysis using optical emission spectroscopy (OES) and hardness measurements using Vickers hardness numbers and a load of 5kg, HV5.

The grain boundary corrosion susceptibility was determined according to ASTM 267-85 Practice A, i.e. oxalic acid etching. Additional measurements of the degree of sensitization using the double-loop electrochemical potentiokinetic reactivation technique, DL-EPR, were performed as part of Finnish Reactor Safety Program SAFIR2014, in the ENVIS-project, "Environmental influence of cracking susceptibility and ageing of nuclear materials".

4. RESULTS

The visual inspection revealed that the pipe with the leak was a (axially) welded pipe (material 1), while the pipe on the other side of the assembly weld was a seamless pipe (material 2), Figure 1. An about 15 mm long crack was observed at a distance of about 8 – 11 mm from the fusion line in material 1, Figure 2. The crack extended up to the cut surface, so only a part of the crack was located in the investigated pipe section. The width of the root of the assembly weld was larger at the location of the crack than elsewhere, obviously as a consequence of the performed re-welding due to the weld defects observed during the assembly welding. A few millimeter long crack was observed next to the cut surface also in material 2. This crack was at a distance of about 8 mm from the fusion line.

The chemical composition of the materials, 1 (with the leak) and 2 (on the opposite side of the weld) are presented in Table 1. The carbon content of the materials 1 and 2 is relatively high, 0.038 and 0.040%, respectively.

The macroscopic crack in material 1, causing the leak, comprise of several cracks which have coalesced into one, see Figure 3, showing that initiation has occurred at several locations at almost the same distance from the fusion line. The cracking mode is intergranular, with a very small amount of transgranular cracking, Figure 4.

The microstructure of the base materials 1 and 2 is austenitic with a small amount of δ -ferrite. The microstructure of the weld next to the macroscopic crack shows that the weld has not been welded continuously, Figure 5, but re-welding has been performed, in line with given information. This was not

seen in a cross-section outside the crack, showing that the re-welding had been performed only to a part of the circumference, as also the width of the root indicated. However, in this cross-section a mis-alignment between the two pipes is obvious, Figure 6.

The macroscopic crack in material 1 is intergranular and mainly only slightly branched, Figure 7. Close to the crack tip in the investigated cross-section, i.e. at about 60% depth (4.6/7.6mm), the crack grows locally parallel to the pipe surface, i.e., almost perpendicular to the main crack growth direction, Figure 8, in both directions from the main crack. This part of the crack grows along a δ -ferrite stringer, after which cracking continues intergranularly in the austenitic material, perpendicular to the surface. Indications of sensitization in the form of pits at the grain boundaries, obviously from carbides removed from the grain boundaries during specimen manufacturing were observed next to the crack. Similar observations were observed in material 2, i.e., the short crack was intergranular and indications of sensitization were observed next to the crack. The grain size was slightly larger in at the location of the crack compared to either side further away from the crack.

Oxalic acid etching of a cross-section close to the cracked region, but still outside it, revealed grain boundary attack, indicating sensitization, Figure 9, only between about 6 and 12 mm from the fusion line, Figure 6. The DL-EPR measurements, measured from slices cut parallel to the fusion line, Figure 10, showed a maximum degree of sensitization at a distance of 6 mm from the fusion line, Figure 11.

The following was done at the plant after the detection of the leak and the immediate repair work. In order to prevent new cracks that leak through in similar assembly welds in the steam lines replaced with stainless steel in the 1980's, the welding protocols of each installation weld in these steam lines were reviewed. As the sensitization was assumed to be caused by several re-weldings, all welds that had been re-welded twice or more, were listed and reviewed by an expert group. Based on this list, a plan for NDT-inspections for potentially sensitized welds was done. The inspections will be done in stages during the yearly outages. The steam lines are covered with insulation and are not accessible during operation, which sets restraints for the inspection work and enables cracks growing undetected until leak.

This IGSCC case has been noted in an applicable expert group at the power plant, and a similar investigation for susceptible welds on the sister unit will be carried out. The expert group is also responsible for the long term monitoring of this case and its possible consequences.

5. DISCUSSION

The leak in the steam line was caused by intergranular stress corrosion cracking in a sensitized Type 304 stainless steel material. Stress corrosion cracking is a consequence of a susceptible material, a stress and an oxidizing environment. Sensitization is the most common reason for IGSCC in stainless steels, although not that common anymore, due to remedies applied in the plants concerning all main affecting parameters, i.e., material, environment and stress. The re-welding during the assembly weld has obviously resulted in increased residual stresses. The environment in the pipe line is an oxidizing steam-water mixture.

Re-welding during the assembly of the pipe section has obviously resulted in higher than typical (without re-welding) residual stresses. The mis-alignment, observed next to the cracked region cause high stresses, and may be the reason for the initial defects in the weld requiring re-welding during the assembly. Further, thinner wall thickness (here 8 mm) compared to thicker, typical for primary piping (~20 mm) results in higher residual axial stresses [7].

A water-steam environment is typically less clean, i.e. more aggressive for IGSCC initiation and growth compared to 288°C primary BWR water. The water in the water-steam mixture contains impurities from the primary water. The steam is, however, clean as most impurities are non-volatile. Impurity concentration on the pipe inner surfaces may increase due to water condensation. These impurities are not removed from the surfaces, i.e., if the condensate vaporizes, the impurities are left behind, and thus

concentrate with time. The possible role of impurities could not be confirmed in the performed investigations as the pipe had been decontaminated at the plant.

That the leak was observed after 30 years of operation indicates that something has increased the initiation and crack growth susceptibility of the pipe line during the long term operation. Sensitization can occur during welding, and grow during long term operation due to LTS. The relatively high carbon content of the pipe materials has increased their susceptibility to sensitization. This, together with a high heat input, which is typically used during re-welding to ascertain a flawless weld, has resulted in the sensitization. LTS is not considered to have an outstanding role in this case due to the low operating temperature of 170°C and consequent very slow diffusion rate [8]. The location of the crack is further away from the fusion line than what is typically observed for sensitized primary piping in BWR/NWC conditions. The typical distance of IGSCC in sensitized stainless steel primary piping is about 3-5 mm, as a consequence of a peak location of the residual stress and sensitization profiles in pipes with a thickness of about 18-20 mm. In this case, the pipe wall thickness is 8 mm, and the cracks in both materials are >8 mm from the fusion line. Sensitization will have a peak at some distance from the fusion line, which is dictated by the temperature profile (input heat and cooling rate). A higher heat input will move the location with maximum degree of sensitization further away from the fusion line compared to a situation where the heat input is lower. This is obviously also the reason the EPR-results, showing a maximum degree of sensitization at a smaller distance from the fusion line compared to the location of the cracking. The EPR-measurements were performed next to the cracked area, i.e., also outside the re-welded region, where the degree of sensitization would be smaller as well as the distance of the peak would be closer to the fusion line due to the smaller heat input compared to the re-welded area with a higher total heat input. Further, the heat will spread to larger distances from the fusion line in a pipe with smaller wall thickness, i.e. in a less massive component. In thick pipes, the heat will spread more also in the depth direction of the pipe, and the larger mass of the structure will have a higher cooling effect compared to a thinner pipe.

Several investigations have shown that dynamic loading is required for SCC initiation, although sustained growth can be maintained in laboratory experiments at constant load [9]. The BWR plant in question has a very high utilization rate, and a low amount of shut-downs / start-ups and transients, typically only one shut-down and start-up per year during the yearly outage. It is highly likely that the dynamic loading during start-ups due to thermal strains has affected initiation and finally resulted in a leak after many years of operation. Deformation is also known to promote IGSCC initiation and growth. A small surface deformation will always be present in as-fabricated pipes, but no indications of additional or heavy surface deformation were observed on the inner surface of the pipe. The absence of excessive deformation has obviously prolonged the time of crack initiation.

Finally, the crack growth rates of sensitized stainless steels are higher at a lower than maximum BWR operating temperature, and peak rates are measured at about 200°C with about 4 times higher CGRs compared to those at 288°C, at high potential [10].

Thus, although rather few IGSCC cases have been reported at temperatures below 288°C, there are several factors increasing the IGSCC risk at a lower temperature. Therefore it is important to include stainless steel components and structures, operating at a lower than maximum temperature, in the evaluation of potential risk for IGSCC.

6. CONCLUSIONS

The leak in the steam line at a BWR operating under normal water conditions was caused by IGSCC in a sensitized, relatively high carbon (0.04%), Type 304 stainless steel after about 30 years of operation. The leak occurred at a position where re-welding had been performed during the assembly welding. This has increased the residual stresses at the location. The high heat input during the assembly re-welding caused sensitization of the material, increasing the susceptibility to IGSCC. Further, IGSCC crack growth rate is higher at about 200°C (the operating temperature for the steam line in question is 170°C) compared to

that at 288°C. Further, water-steam environment is typically less pure, i.e. more aggressive for IGSCC compared to primary BWR water due to condensation on the pipe inner surfaces and consequent concentration of impurities with time.

It is therefore important to include also stainless steel components and structures operating at lower than 288°C temperatures in the IGSCC risk evaluations and inspections.

7. ACKNOWLEDGEMENTS

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Table 1. Chemical composition (wt-%) of the investigated materials

Material	C	Si	Mn	S	P	Cr	Ni	Mo
1	0.038	0.44	1.54	0.007	0.030	18.2	8.67	0.07
2	0.040	0.46	1.54	0.006	0.031	18.1	8.71	0.07

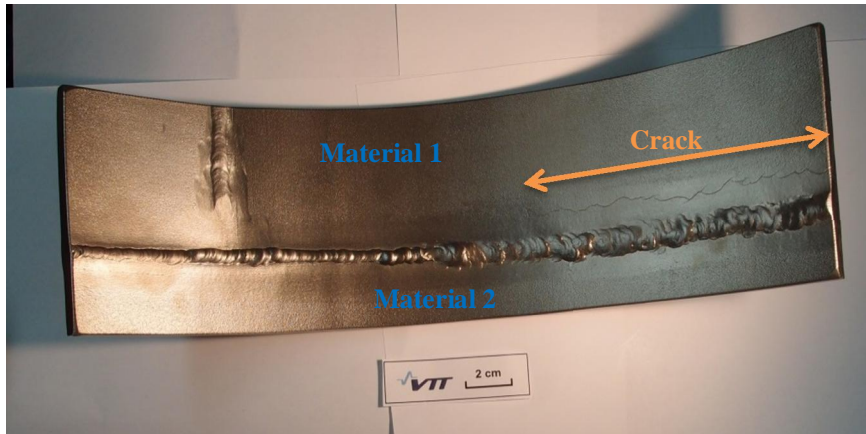


Figure 1. Photograph of the pipe section with a leak in material 1.

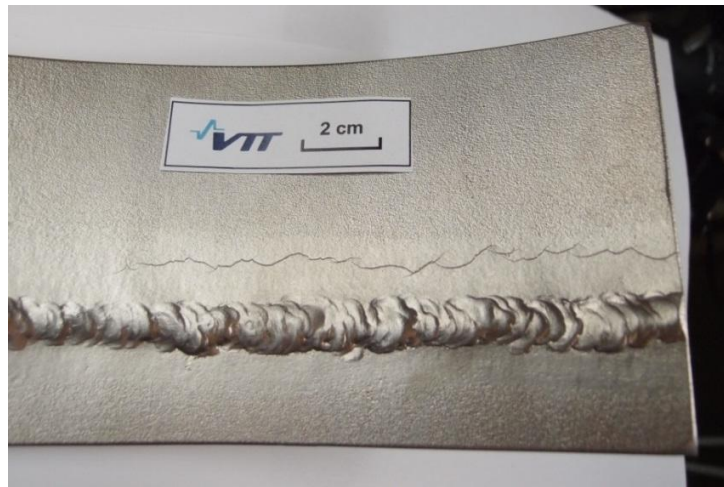


Figure 2. Close-up of the crack causing the leak in material 1.



Figure 3. Photograph of the fracture surface of a part of the crack in material 1.

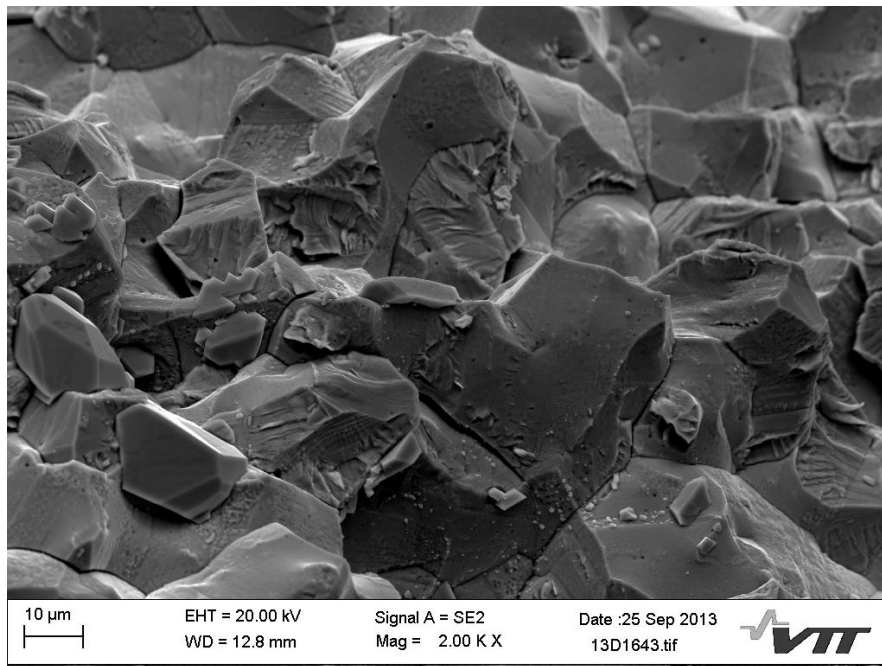


Figure 4. Mainly intergranular cracking of the crack causing a leak in material 1.

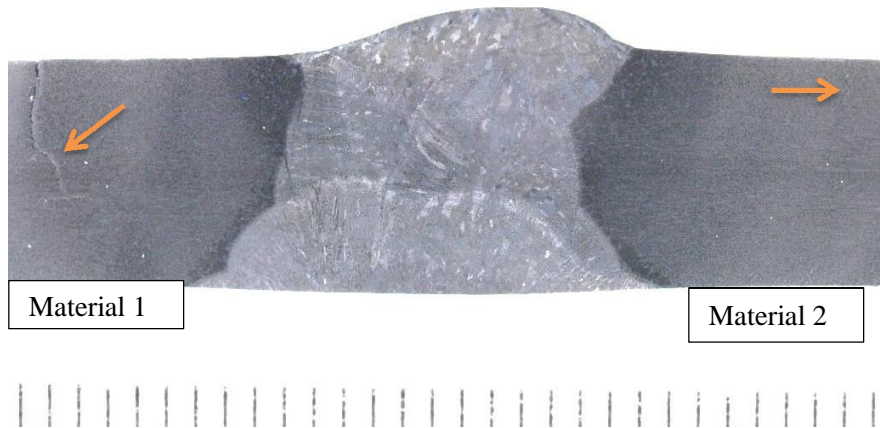


Figure 5. Macrograph of a cross-section, showing cracks both in materials 1 and 2, as indicated with arrows.



Figure 6. Macrograph of a cross-section close to the cracked region after oxalic acid etching. A clear mis-alignment between the pipes is seen. The region where grain boundary attack was observed in the two materials is indicated in the picture.

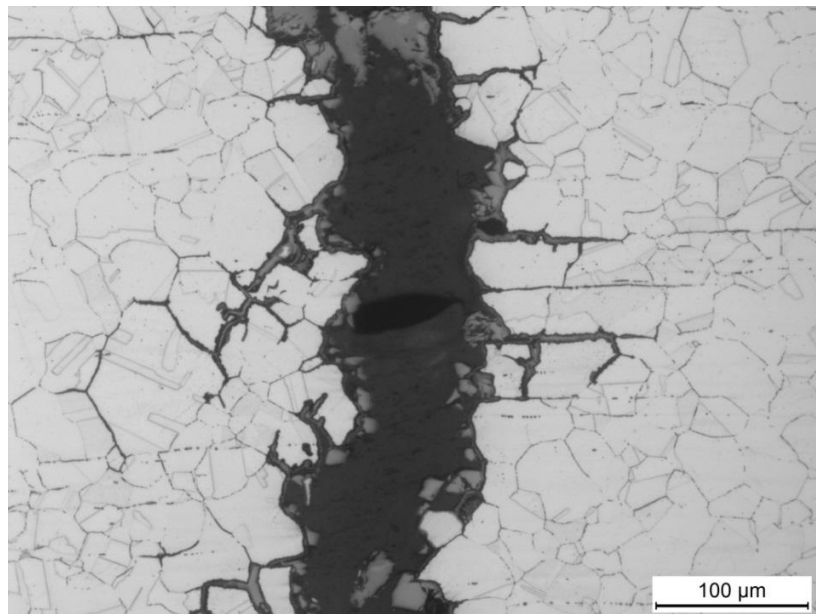


Figure 7. Intergranular cracking in material 1.

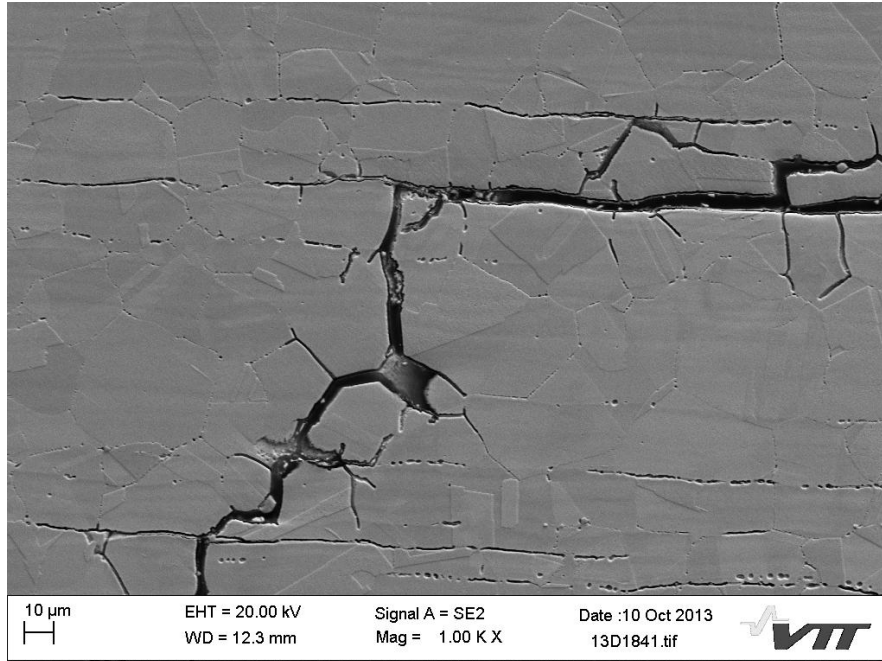


Figure 8. Locally, the intergranular crack grows along a δ -ferrite stringer.

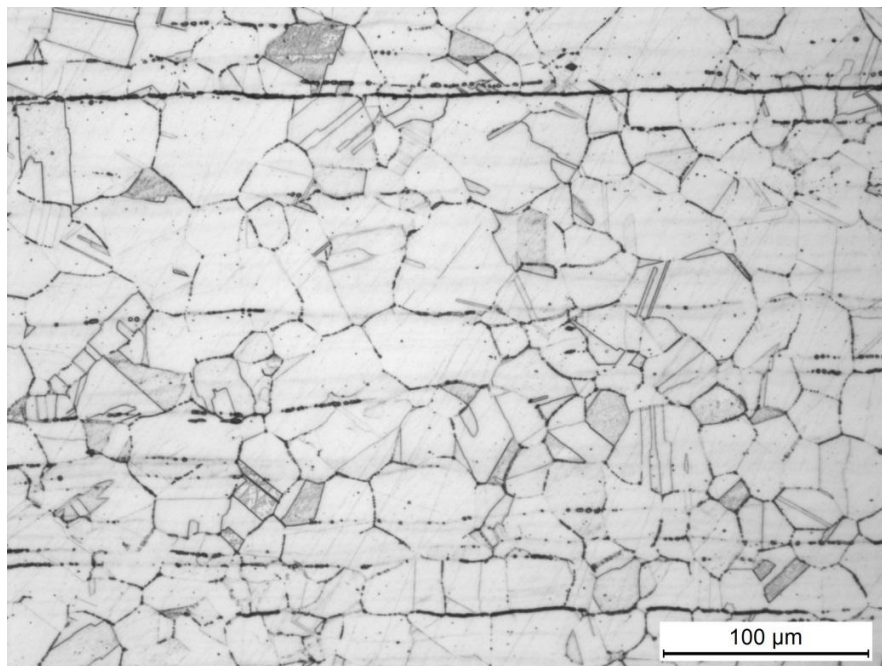


Figure 9. Microstructure of material 1 after oxalic acid etching showing grain boundary attack, which, however, is not fully continuous.

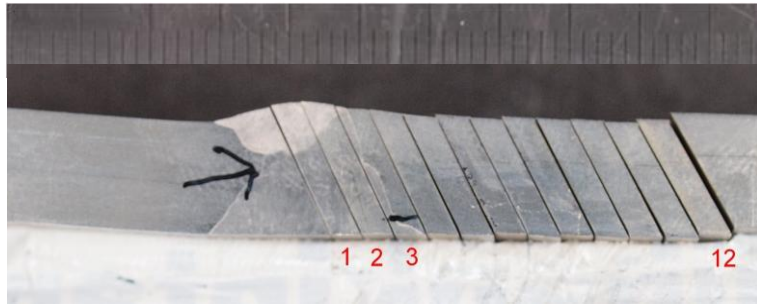


Figure 10. Photograph showing the cutting of the slices for DL-EPR measurements.

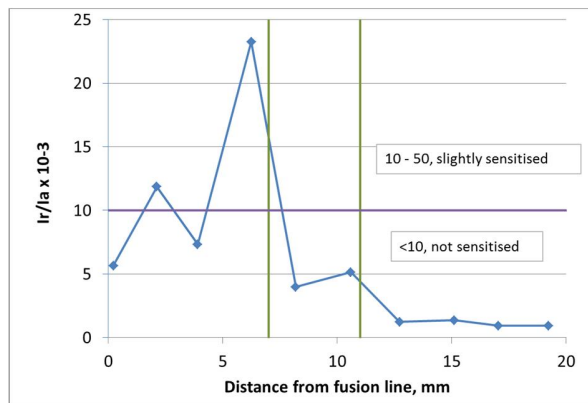


Figure 11. DL-EPR results as a function of distance from the fusion line. The vertical lines indicate the region with cracking.