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Development and production of test specimens to evaluate an inspection issue

Abstract

Assessing the reliability of non-destructive evaluation (NDE) is quite challenging, because it depends on a multitude of different factors ranging from physical aspects of the used technology to human factors. Generally, the reliability can only be assessed via practical trials where the inspection is performed on a known, flawed sample and reliability is judged by comparing the acquired inspection result with the known state of the sample. Consequently, it is vital to have representative test specimens and representative cracks in order to get reliable information about NDE reliability. Over the years, several techniques have been developed to manufacture representative flawed test samples. The development has led to increasing representativeness in test specimens. In recent years the most significant trend has been the increased use of "grown cracks", which currently offer the best representativeness available. However, the available techniques are still not used to their full potential so that additional guidance and experience are needed to improve practical trials.

1. Introduction

The reliability of non-destructive evaluation (NDE) depends on a multitude of different factors. These range from physical aspects of the used technology (e. g. wavelength of ultrasound) to application issues (e. g. probe coupling or scanning coverage) and human factors (e. g. inspector training and stress or time pressure during inspection). Due to this complexity, the only practical way to assess inspection reliability and to confirm that the inspection procedure functions as intended is by using practical trials. In practical trials the inspection is performed on a known, flawed sample and reliability is judged by comparing the acquired inspection result with the known state of the sample. However, the practical trials themselves have proven somewhat challenging to arrange. In particular, it is paramount that the inspection arrangement and flawed sample used are representative of a real inspection situation. Representative flawed samples are vital in order to assess NDE reliability and to get necessary feedback for improving NDE.

The first flawed samples used applied mechanically-machined flaws, i. e. flat bottom holes, saw cuts and later electro discharge machining (EDM) notches. They can be easily manufactured to tight tolerances. However, as NDE methods and requirements evolved, it soon became apparent that their representativeness was not good enough to estimate true NDE performance. Mechanical notches are still used in samples used, for example, for signal calibration where representativeness to true cracks is not important. Also, use of notches to estimate NDE performance is still justified in cases where no other flaw type can be manufactured. Here, of course, the justification becomes increasingly difficult, as there is no direct information about the true performance of the inspection. If an indication is actually found, the test samples with notches provide no help to explain it and additional information is then required. Sometimes this is covered by additional technical justification to justify the difference between NDE response obtained and the performance seen with unrealistic notches. Eventually, getting confidence in unclear indication issues may require a post-inspection open trial with realistic, natural cracks.

To improve on the mechanical notches, various welded flaw simulations have been developed. They are manufactured, in simple terms, by either implanting an existing flaw by welding to the sample, or by inducing cracking of the weld by carefully chosen weld parameters. These simulations offer closer approximation to real cracks, as the crack propagation is tortuous and some other crack parameters resemble true service-induced cracks. Welded flaw simulations have been extensively used in inspection qualifications during the last decades. However, significant discrepancies remain between true, service-induced cracks and welded flaw simulation as the weld metal introduced in the production process may affect inspection in an unpredictable manner. Also, the flaw characteristics tend to differ from natural cracks, for example, the crack opening tends to be bigger and most importantly realistic crack tip conditions are not attained.

Consequently, inferring real world performance is more difficult and the inspectors get less experience with true cracks. On the contrary, inspectors get experience, which may lead to unrealistic confidence on the inspectors skills or capability of the technique. Also, the technical justification required to address the differences to natural cracks makes the samples more case-specific. There's a risk in redoing the qualification if the justification later proves invalid.

Not surprisingly, as NDE methods and requirements have developed, need for better flaws increased especially in cases that are sensitive to weld material (e. g. austenitic materials or eddy current [EC] inspections) or critical crack characteristics (e. g. TOFD-sizing). To further improve from the welded flaw simulations, techniques were developed to induce real cracks without welding. These methods are called "grown cracks" due to the fact that they rely on the same natural growth mechanism that might be responsible for growth of the service-induced cracks. With these methods, crack growth is accelerated and controlled to facilitate production of cracks. The use of test blocks with natural grown cracks has several advantages: the performance of the NDE system is shown with minimal uncertainties and inspectors get experience on true cracks and know what to expect during in-service inspections (ISIs). There is no room for discussion about the validity of the samples.

In recent years such technology has matured and has been tried and tested [1]–[5]. Capability of the technique to produce realistic, representative flaws has been analysed by comparing the crack characteristics with the characteristics measured from service-induced flaws. This comparison has been made against measured values from service-induced flaws reported by Wåle [6, 7]. Comparison done, e. g. in [5] for the crack opening values, has indicated that the flaws produced by the new technique are very representative for most of the service-induced flaws, when used as a reflector for different NDE development, training and qualification purposes.

The following figure (Fig. 1) shows a comparison of some often used defect types: EDM notches, welded crack simulations and grown cracks as well as a true crack from the literature.

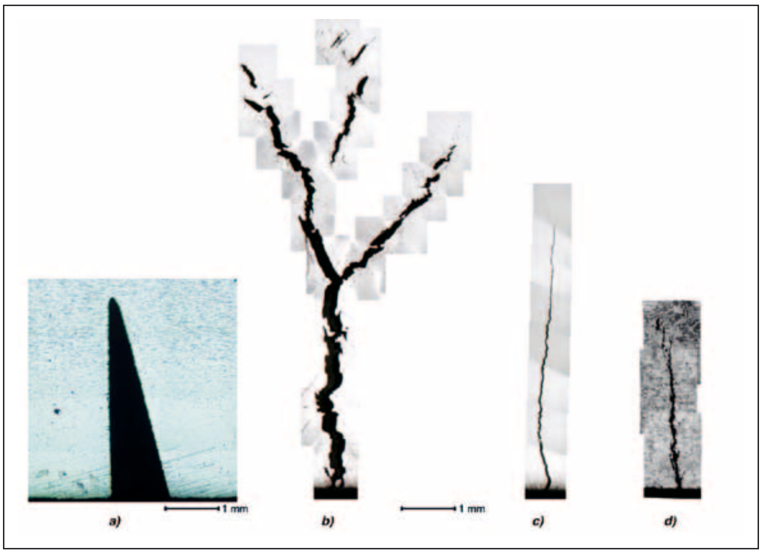


Fig. 1:
EDM notch (a), welded crack simulation (b) [3], grown crack (c) [3] and true crack (d) from the literature [8]

Production methods to produce grown cracks have been under significant scrutiny and they have now been validated and qualified for use in inspection qualification in various countries.

Due to the investigations done on grown cracks, there is now much new information available on applicability of different artificial defects [2, 3]. Various essential characteristics of both service-induced cracks [6, 7] and artificially produced grown cracks have been studied and documented [5]. Consequently, a sound body of technical information is now available for use in inspection qualification. However, this information is currently not used to its full potential.

The nature of the technology is to accelerate a natural damage mechanism in a controlled way and hence cracks grow only as allowed by nature. In practice the crack growth follows the weakest path through the microstructure in the intended location. This is clearly an advantage of the technology. However, if one has applied other technologies such as EDM notches or welded flaws earlier, and placed them freely, there may be a need to change the way of designing flaw specifications to follow more the natural crack growth. Such cases have been, for example, straight cracks specified in the fusion line of a winding weld where the true crack growth follows the shape of the fusion line. Or, for example, a skew of the flaw has been specified in geometry, where no skew can exist for a natural crack. So, as with all new technologies, though there is a lot of potential, one should be aware that in applying the new technology to new cases, different aspects showing inspection technique related limitations and a respective need for improvement in applying the technology may arise. Such things are part of the learning curve of applying the new technology and they also show that there is a need to change part of the current way of specifying defects used.

1.1 Current state of the art

The controllability of the flaw manufacturing technology is one crucial aspect when selecting flaw production technology for NDE qualification purposes. This is due to the fact that only by controlled manufacturing can one get repeatedly known flaw sizes and reproduce essential flaw characteristics. The most controllable of the flaw manufacturing techniques is the electro discharge machining. However, it does not reproduce any realistic characteristics for the flaws. For the other techniques, representativeness is better, but a variation can be seen in the production controllability from bad to good. Representativeness and controllability of different flaw manufacturing techniques are shown in the following figure (Fig. 2).

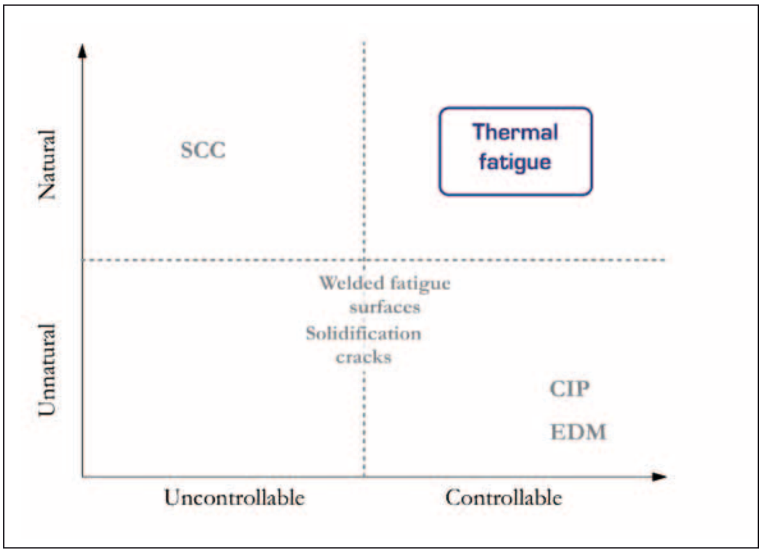


Fig. 2: Representativeness vs. controllability of different flaw types SCC = Stress Corrosion Cracking CIP = Cold Isostatic Pressing of a notch

Production of EDM flaws may meet limitations in the specimen geometry and weight due to challenges in handling and access of the intended location. Furthermore, all the flaws produced by EDM are surface breaking. With this technique, flaws can be produced in most of the metallic materials.

The welding-based procedures have the limitation that they induce extra weld material in the specimen. Furthermore, welding-based flaw manufacturing, if applied to ready-made specimens, is done on purpose-machined grooves, or it has to be done during the manufacturing of the specimen. Hence, these techniques cannot be applied to ready-made specimens without modifying the specimen with an additional weld. By welding-based techniques, flaws can be produced in all the materials that can be welded.

There has been considerable development on grown crack production techniques relying on stress corrosion cracking. Developed stress corrosion cracking techniques can be applied to limited size and shape of specimens due to the fact that an external loading is needed to create the stresses. Such external stresses are not to induce full-scale mock-ups with complex geometry. Furthermore, due to the nature of the damage mechanism itself, control of the flaw sizes is quite rough. All the cracks grown by stress corrosion techniques are surface-breaking. This technique is limited to materials where stress corrosion damage mechanisms can occur.

The nature of the thermal fatigue crack growth technology allows surface-breaking cracks to be produced. Size of produced natural cracks can be controlled accurately. Furthermore, the location where the crack is to be manufactured must be attainable (i. e. the loading tool must fit the location). This prevents crack production, for example, to the inner diameter (ID) of very small tubes. Currently the smallest tube ID where cracks have been produced is about 16 mm. While this technique is applicable to a wide variety of materials, there are also some materials that present a challenge. Currently cracks cannot be manufactured, e. g., to copper and aluminium.

The use of grown cracks based on the thermal fatigue production process has increased markedly during the last few years. Furthermore, the amount of different applications has become larger thus covering today most of the NDE inspection techniques and targets in the nuclear field.

1.2 ENIQ methodology

Today, rules and requirements for the inspection qualification are introduced increasingly in the nuclear industry in different countries. Very rapid development in the requirements for the inspection qualification can be seen in many countries. Though they still vary from country to country, an effort to harmonize different requirements has been made. One common guideline is the set of recommended practices published by the European Network for Inspection Qualification (ENIQ) [9]–[18] giving general guidelines for inspection qualification. ENIQ methodology is, to a certain degree, followed by most European countries.

The starting point of the ENIQ methodology is the "input information" dossier that defines the inspection case and includes information about component and flaw types expected under service conditions. Input information dossier is typically prepared by the plant operator having the best information on the pertinent damage mechanisms. Crack growth mechanisms as well as critical flaw sizes are defined in the input information. The inspection procedure is defined based on this input information, usually by the inspection vendor. When these two are available, a technical justification is prepared. This document takes the relevant data from input information and inspection procedure and defines the most important parameters for successful inspection. With use of the technical justification, test blocks can focus on testing the most important challenges of the inspection.

Different aspects of the practical trials are accomplished by the technical justification. However, the technical justification dossier has also some problems related to test block manufacturing and defect selection. The problem is that the guidance to test block manufacturing comes only in the end of the technical justification. Consequently, the defect specifications tend to be dominated by inspection considerations and information relating to crack characteristics to be expected in real life is not well preserved. In fact, the ENIQ methodology does not currently facilitate selection of defects very well. Also, when the test blocks and defects are tightly coupled with the technical justification, they become specific to the qualification at hand. This is more widely discussed in the reference [19].

ENIQ methodology mentions use of test blocks with defects in three phases: laboratory samples, open trials and blind tests. The purpose of the laboratory samples is to give background information and supporting evidence for the technical justification. The purpose of the open trials is to show that the technique is able to achieve the performance defined in the technical justification. The purpose of the blind trials is to demonstrate that the personnel are able to correctly apply the technique and judge its results. To fulfil these purposes, the defects in all test blocks should give a representative response (in terms of essential characteristics) as compared to the defects defined in the input information.

1.2.1 Current way of selecting different flaw types (under ENIQ methodology)

In a national example of ENIQ-based methodology followed in Finland for the qualification, the justification of the used flaws relies heavily on the experience of the involved parties. There is no clear set of requirements for flaws. Instead, the applicability of defect types for each case is defined in discussion between the qualification body and the operator, that is, requirements are redetermined for each case. When limited experience is available, defects chosen may be rejected during fingerprinting, for example, based on unrealistic response or unacceptable disturbances.

However, to clarify the process of using mock-ups with representative flaws, there should be clear requirements set for the flaw characteristics in the ENIQ-recommended practises, as well as in the authority requirements. Such requirements should be for the essential flaw characteristics as, for example, crack opening, crack tip radius, fracture surface roughness, amount of turns and flaw tilt angle. The most important for the range of values of different characteristics is that it should be based on real measured values from service-induced flaws.

Quantified requirements would induce measurement of essential characteristics of each flaw type used, together with statistical analysis on the reproducibility and manufacturing tolerance of the characteristics in question.

2. Application case examples

Two different, real-world application cases are presented. These show the benefits obtained by using advanced realistic crack types. In both cases, an earlier qualified and accepted inspection technique was applied with an assumption that it should give reliable results. However, in both cases an indication obtained from the actual inspection, had left unclear the origin of the indication. Therefore, additional studies of the inspection issue had to be performed with realistic natural cracks produced in the actual specimens.

To solve the unclear NDE indication obtained in both cases a post-inspection open trial was done with realistic grown cracks. These were produced in real specimens with the material and geometry similar to the actual inspection target.

2.1 E.ON reactor pressure vessel nozzle inspection issue

In the nuclear power plant of E.ON in Brokdorf, Germany, non-destructive inspection of dissimilar welds is an important part of the inspection program in refuelling outages in nuclear power plants. The inspection of the inner weld surface in the reactor pressure vessel head nozzles of German PWR plants is complicated by geometrical constriction. This dissimilar metal weld is accessible only through a 1 mm thick gap, which the eddy current probe must pass through. For this inspection a new eddy current technique had to be developed. Due to the geometrical limitations, the probe design had to ensure an extremely flat probe. The qualification of the inspection technique was performed with a test specimen made of a real nozzle using EDM notches as simulation of cracks according to applicable rules. Qualification was accepted before applying the inspection technique for inspections during the outage of the plant in 2007.

During the ISI in 2007, an indication was found close to the austenitic side of the dissimilar weld in one nozzle. The signal was not within the phase range of defects detected in the qualification and the signature was totally different from the signal of notches. The circumferential extent was small in respect to the length of the weld. So, the indication was not classified as a defect signal, nor was it a clear geometrical indication. It was decided to make further investigation to find out the reason of the signal.

One of the points to study in this investigation was to find out the difference between notch signals and the signals of real cracks. The next aim was to develop a visual technique able to inspect the inner weld surface through the 1 mm gap. A test specimen was made using an original nozzle made of vintage material. Due to need of realistic cracks and existing sample, in-situ grown cracks had to be used. Trueflaw was ordered to manufacture cracks in this new specimen as well as to make different EDM notches and notch fields as references.

E.ON supplied an original nozzle to Trueflaw to be used as a test block. Part of the test block area was marked for validation. Trueflaw produced validation cracks of intended size to this area. The area containing the validation cracks was then cut out from the tube using EDM and the cracks destructively examined to reveal the true crack depth. As the Trueflaw technology was used by E.ON for the first time, E.ON and a consultant expert of the authority (TÜV) visited Trueflaw to follow the progress. Subsequent to the accepted validation result, the final cracks were manufactured and the sample supplied to E.ON.

There was a requirement for the crack to be a natural one with realistic opening profile. Due to this requirement, in addition to the normal crack validation, a cross-sectional sample was made to measure the crack opening profile in the depth direction. The next figure (Fig. 3) shows a picture of the cross-sectional sample together with the opening profile measured.

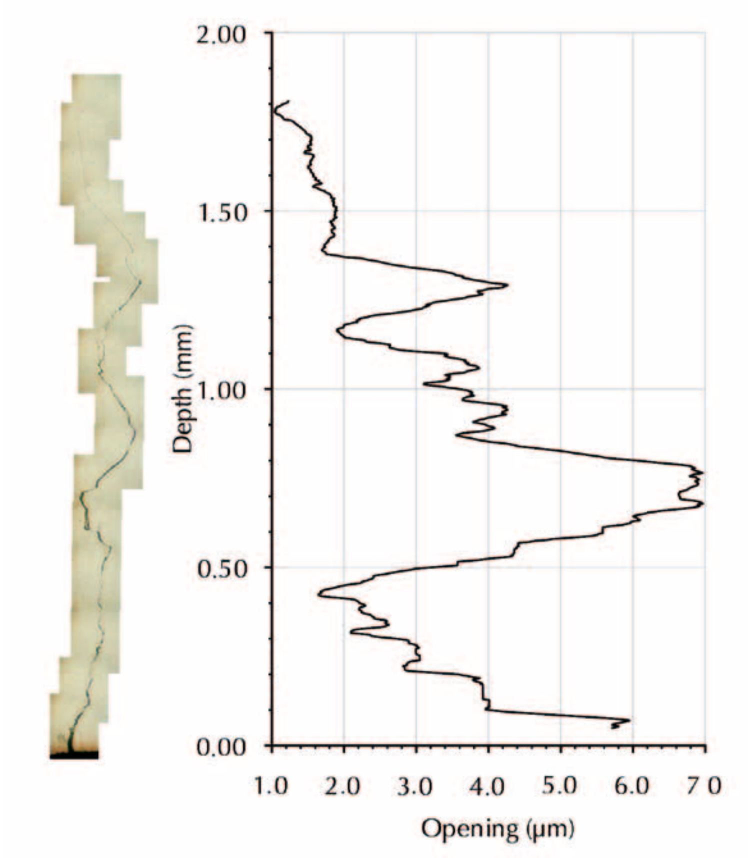


Fig. 3: Crack opening profile in depth direction together with the measured opening profile values

With the manufactured cracks, the eddy current system qualification was repeated, and the phase range for defects could basically be verified with the signal being reduced at the edges. With a crack having a secondary crack close to it, it could be proved that no phase shift occurs, when more than one crack is in the area of influence of the probe. The new developed visual inspection technique (using special optical components and a CCD-chip together with an optical fibre lighting) was qualified as well. The applicability of the very small high resolution video probe (to be used in the gap of around 1 mm width) for the detection of cracks even from problematic view angles could be verified clearly with the natural cracks delivered by Trueflaw.

In the 2008 outage a second inspection of the reactor head penetration with the optimized qualification of the eddy current inspection and the visual inspection was made. The signal was found unchanged. It could be confirmed that the reason for the indication was of geometrical nature. In conclusion, a crack in the component could be excluded.

Furthermore, inspection processes were requalified and accepted for further use. With the real cracks used, a complex problem that otherwise would have led to extended discussions and technical justifications with, for example, the need of disassembling the control rod drive mechanism, was solved.

2.2 Axpo CRDH inspection issue

In the nuclear power plants operated by the Axpo an EC inspection technique is used to inspect dissimilar metal weld in the reactor pressure vessel upper head penetrations. Axpo had successfully qualified the inspection technique before the planned outage of the year 2008. Qualification has been carried out by samples with EDM notches.

However, during ISI of the head penetrations in the outage 2008, problems arose due to unanticipated geometry of the target area. The ID contour, contrary to the expectation, was not smooth. It had a small counterbore, that prohibited the eddy current testing (ET) probe to have constant contact. As a result, a disturbing indication along the circumference was obtained. This indication, caused by the poor coupling of the eddy current probe, could mask possible real indications.

The regulator did not accept the inspection results, and required the plant to optimize the inspection technique to overcome the geometric restriction present. Consequently, when the optimization of the technique has been done, both the qualification and the performed in-service inspections have to be redone. The upper head shall be replaced in about four years, so the developed system will have a short useful life and the effort planned accordingly.

So, it was decided first to apply a qualified moulding technique on three penetrations to determine the ID contour. This investigation showed that there is an inner diameter difference between 1.5 and 2 mm and that the counterbores have different steepness. The next figure (Fig. 4) shows a drawing of the geometry based on the moulding result. The next step was to manufacture a sample representing the geometry of the real penetrations. Realistic flaws were needed to achieve reliable inspection results. The sample had to contain realistic cracks in different positions in the weld area. Furthermore, as the sample was already finished, the applied production technology had to deal with this.

The plant decided to use Trueflaw cracks based on the criteria that realistic cracks were needed and they had to be put in a ready-made sample. Two different crack depths were specified: 1 mm and 3 mm. The 1 mm depth was for the ET inspection and 3 mm for the additional UT sizing technique. As the moulding technique was also used for the in-service inspections, this sample was to be used as a verification test of the technique's capability to show that there are no cracks in the penetrations inspected by the moulding technique. The next figures (Fig. 5 to 8) show examples of penetrant testing (PT) done (by Trueflaw) and the corresponding moulding inspection result. Moulding inspection results are photographs of the replica taken from the sample.

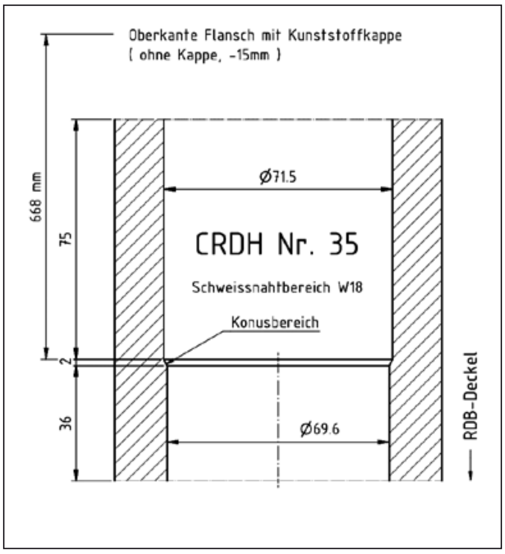
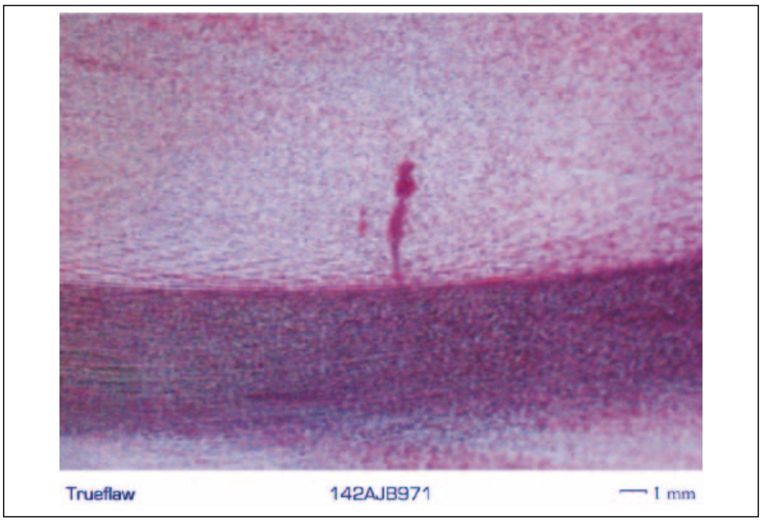


Fig. 4: Example of a penetration ID contour



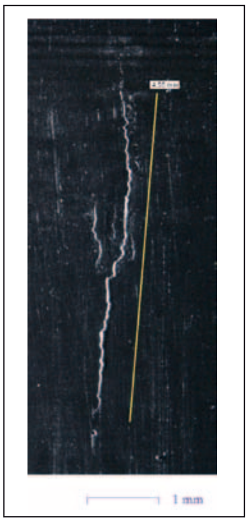
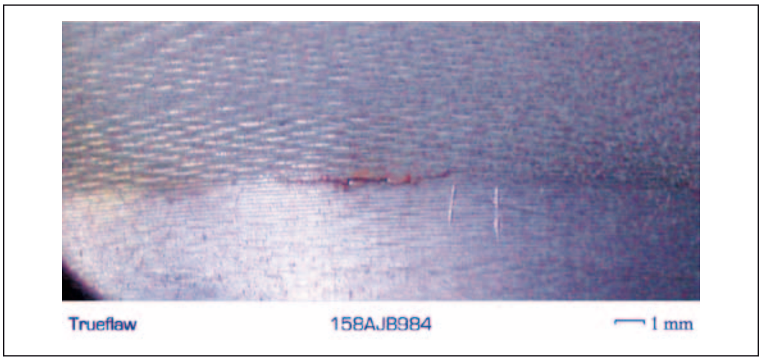


Fig. 5 and 6:
PT indication with corresponding moulding indication (with secondary crack)



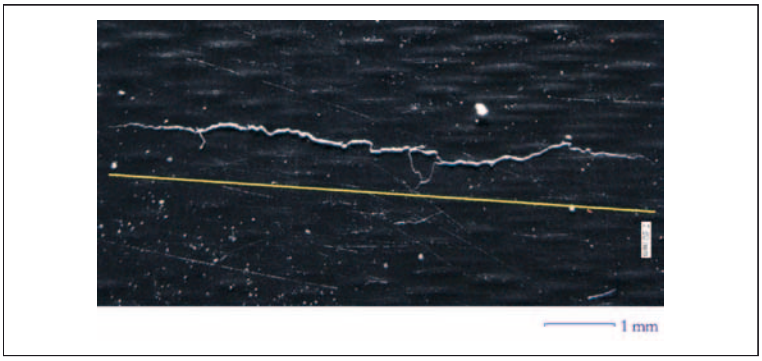


Fig. 7 and 8:
PT indication with corresponding moulding indication

In the near future the sample shall be inspected by the ISI technique used in 2008. The plant expects that it will be possible to show that cracks would have been detected even with the non-optimized inspection technique and that the already performed inspections of year 2008 can be accepted. And the authority questioned performance of the inspection techniques would be confirmed. Thus the real cracks used in an additional open development sample could solve a complex problem that otherwise would have led to extensive rework with a part that will soon be replaced. However, if a complete new qualification should be required, further samples with Trueflaw cracks will be used.

3. Conclusions

Assessing NDE reliability through representative practical trials remains quite a challenging task. Over the years, the techniques to produce representative flawed samples have been developed. This has led to increasing representativeness in test specimens. In recent years the most significant trend has been the increased use of "grown cracks" which currently offer the best representativeness available.

The available techniques are not currently used to their full potential. Consequently, additional guidance and experience is needed to improve practical trials. In particular, clear guidelines for justifying used defects and requirements for defects are needed in the ENIQ. Also, sharing practical experience between users, like the two cases presented here, is important to promote efficient use of different flaw types. The current experience of using modern grown cracks ranges from full qualification cases with both open and blind trials, NDE development for new inspection technologies, reference and calibration samples, and samples for training of inspectors. Grown cracks have been used for various NDE techniques covering ultrasonic, eddy current, dye penetrant, magnetic particle, visual and radiographic testing techniques (both film-based and digital radiography). Also grown cracks have proved valuable in developing emerging techniques such as thermosonic and x-ray diffraction inspection techniques.

In conclusion, the use of the more advanced defect manufacturing techniques gives inspectors experience on real cracks and allows tuning the procedure to find and size real cracks. The test blocks are more generic and can be used for various NDT methods and procedures, thus avoiding rework when methods or requirements change or new information becomes available.

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