Proposed improvements for use of different qualification defect types - three generations of defects

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INTRODUCTION

The reliability of non-destructive examination depends on 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). To assess the vital issue of NDE reliability, qualification of used methods is nowadays required in most countries for nuclear inspections. The exact manner in which the qualification is implemented varies, but in most cases qualification includes practical trials to some extend to verify and confirm that the inspection procedure functions as intended. In practical trials the inspection is performed on a known, flawed test piece and reliability is judged by comparing the acquired inspection result with known state of the test piece. However, practical trials themselves have proven somewhat challenging to arrange. In particular, it is rather challenging to show that the inspection arrangement and flawed test piece used are representative to real inspection situation. In practice, quality and applicability of the qualification is heavily dependent on the quality of the used test pieces.

Over the years, number of different approaches has been used to produce the flawed test pieces needed. Both the inspection techniques and qualification practices have developed. Consequently, both the quality and requirements for test pieces have developed.

The first flawed samples contained mechanically machined flaws, i.e. flat bottom holes, saw cuts and later EDM (electro-discharge machined) notches. We call these "1st generation flaws" (later "1G"). These can be easily manufactured to tight tolerances. However, as NDE methods and requirements developed, it soon became apparent that their representativeness was not good enough to estimate true NDE performance. Mechanical notches are still used, for example, for signal calibration where representativeness to true cracks is not important.

To improve on the mechanical notches, various welded flaw simulations have been developed. We call these "2nd generation flaws" (later "2G"). These are manufactured, in simple terms, by either implanting an existing crack by welding to the test piece, or by inducing cracking of the weld by carefully chosen weld parameters (see, e.g.,[1-2]). Most of the flawed test pieces currently in use apply 2nd generation flaws (see, e.g., [3])

These 2G flaws offer closer approximation to real cracks than 1G flaws, 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. 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 realistic cracks tip conditions are not attained.

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 EC-inspections) or critical crack characteristics (e.g. TOFD-sizing). To further improve from the welded flaw simulations, techniques were developed to grow real cracks without welding. These methods can be 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. We call these "3rd generation" flaws (later "3G"). With these methods, natural 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 knowledge what to expect during ISI's. Also, there's no room for discussions about the validity of the samples. On the other hand, manufacturing cost of 3G cracks is generally greater than 2G defects.

The third generation flaws have generally been available since early 2000's. In recent years such technology has matured, tried and tested [4-8]. Capability of the technique to produce realistic, representative flaws has been analysed by comparing the crack characteristics to the characteristics measured from service-induced flaws. This comparison has been made against measured values from service-induced flaws reported by Wåle [9,10]. Comparison done, e.g. in [8] 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. However, the technology is still much less used than first and second generation flaws and thus it's still a "newcomer" in many ways: inspectors have generally not seen these cracks to great extent. 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.

SELECTING ARTIFICIAL DEFECTS

Up until late 1990's the choice to make for test pieces was, in simple terms, to choose optimal combination of first and second generation flaws. Now, however, the range of flaw types has increased and the challenge is to choose optimal combination of first, second and third generation of flaws. There's basically two frameworks which offer guidance to selecting flaws: the ENIQ methodology and ASME code (see Whittle [11] for critical review of ASME and ENIQ). These may be used separately or in conjunction to perform a qualification.

The ASME code (Section XI, Division 1, Appendix VIII, first published in 1989) gives direct guidelines and requirements for the test pieces used (See, e.g. [12] for review on various aspects of the ASME code). The demonstrated performance is based on statistical screening approach; if an examiner identifies 90% of the flaws in the specimen test set and does not exceed 10% false call rate, the examiners propability of passing the qualification is 90%. If the examiner identifies only 50% of the flaws and has false call rate of 30%, passing propability is reduced to 1% [13,14]. Based on the ASME acceptance criteria, the inspector pass probability for various POD's and false call rates can be calculated with monte carlo simulation. Results for such simulations are illustrated in Figure 1. It should be noted, that the curves describe pass probability on per test basis. If candidate is allowed to retake the test, then the combined probability of passing the test differs from the curves shown here (i.e. passing the test becomes significantly easier). However, the pass probabilities shown may give pessimistic view on actual inspector POD: data published from actually gathered performance demonstration test results ([15]) indicates that actual POD values demonstrated by the candidates far exceed estimates given above.

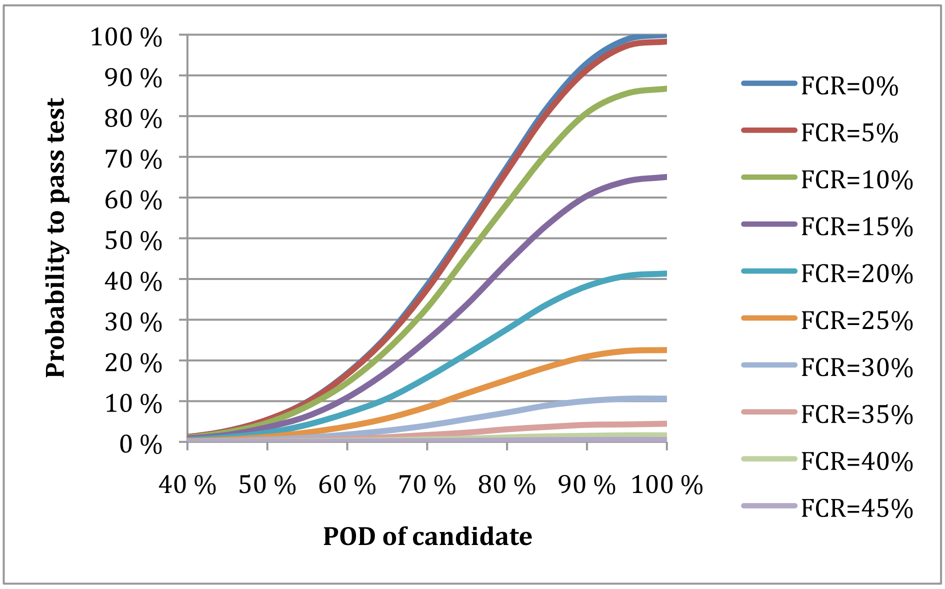

Figure 1. Monte-Carlo simulation for ASME Section XI, Appendix VIII, Supplement 2 detection acceptance criteria (Table VIII-S2-1) with 10 flawed grading units (minimum required). Curves show different false call rates (FCR). Monte-Carlo simulation used 100000 random samples per point (21 million random samples in total).

Appendix VIII includes number of supplements each for different (but generic) inspection type. The flaw types, size distributions and number of flaws are detailed for each inspection type in the corresponding supplement. For example, supplement 10 (dissimilar metal piping welds) gives the following guidance on the flaw types:

...

(a) At least 60% of the flaws shall be cracks and the remainder shall be alternative flaws. Specimens with IGSCC shall be used when available. Alternative flaws shall meet the following requirements:

(1) Alternative flaws, if used, shall provide crack-like reflective characteristics and shall only be used when implantation of cracks would produce spurious reflectors that are uncharacteristic of service-induced flaws.

...

All in all Appendix VIII considers three types of flaws:

i) weld implanted cracks (mechanical fatigue, thermal fatigue or SCC are implicitly assumed to be weld-implanted), i.e., 2G
ii) Alternate flaws (presumably tight notches, "1.5G") and
iii) Notches (1G).

That is, 3G cracks are not considered by the Appendix VIII and/or they are implicitly considered equivalent to 2G weld-implanted cracks. This conclusion is supported by number of papers written soon after the initial release of the Appendix VIII ([16,2]). At the same time, the wording does suggest strong preference to natural cracks and does recognize possible problems with implantation. The problems with sample manufacturing and "less than perfect" test pieces is also identified by Becker [17] in review of Appendix VIII implementation.

The main advantages of ASME qualification are its simplicity of use and generality. On the other hand, it's been criticized [11] for being overly general, providing insufficient verification for inspection reliability and for being costly (due to its heavy reliance on practical trials).

The ENIQ methodology was developed to overcome the perceived shortcomings of the ASME qualification scheme. Its should be noted, that due to it's European roots, the ENIQ methodology gives general guidelines for inspection qualification. Each country can then adapt suitable national implemenation to use. The actual implementations vary considerably.

The starting point of the qualification for the ENIQ is the input information dossier. This contains information about the cracks that are expected in the component. The crack growth mechanisms as well as the critical flaw sizes are defined in the input information. The input information is typically prepared by the plant operator, who has best information on the possible damage mechanisms. Based on this input information, the inspection procedure is defined, usually by the inspection vendor.

When these two are available, a technical justification (TJ) is prepared. It takes the relevant data from input information and inspection procedure and defines the most important parameters for successful inspection. The applicability and performance of the chosen procedure is then justified using previous experimental evidence, modelling parametric studies etc. Finally, guidance is given for the test blocks to be used for open and blind trials in qualification.

So, in broad terms, the generality and simplicity of the ASME code has been replaced with an adaptive approach. For each component, the expected damage mechanisms are assessed and the inspection reliability is assessed on theoretical considerations. The role of practical trials is then, to confirm that the technical justification works as expected (and not to provide statistical evidence of the reliability of the inspection). With use of the technical justification, the test blocks can focus on testing the most important challenges of the inspection and the amount of needed test blocks and defects can be reduced. According to ENIQ, the amount of defects can be further reduced by using worst case -defects. In this case, the most difficult defects from inspection point of view are defined and tested for in the open and blind trials.

The ENIQ methodology has it's own shortcomings that generally mirror those of the ASME code. Whereas for ASME code the statistics give very clear evidence on the proven performance, for the ENIQ the proven performance is more obscure since it's based on both technical justification and practical trials. The recent advances in risk-informed in service inspection (RI-ISI) underline the problem with qualitative demonstrated performance. Some recent advances to quantify demonstrated performance include Bayesian model with relative weights and probabilities assigned to TJ and practical trials based on expert judgement [18-20]. If worst case defects are used to reduce number of test blocks, then reliance on technical justification increases further. Also, qualification is not just a final test of a frozen inspection method, but rather an iterative learning experience were inspectors develop and tune their inspection procedures to increase inspection reliability. Consequently, using worst-case defects focuses development resources on the difficult (but possibly improbable or impossible) defects on the expence of the more likely (but possibly easier) defects.

The ENIQ documents do not give much guidance for flaw selection in test pieces, since this is, generally, considered to be an issue determined in the technical justifications and by the QB. Consequently, the methodology requires very high level of expertise available on damage mechanisms, inspection technology and flaw manufacturing when preparing the technical justification.

Due to the complementing advantages and disadvantages of the ASME code and ENIQ they can be successfully used in conjunction. This is rather counter-intuitive, since ENIQ was develop to overcome the perceived weaknesses in ASME. In practice, this means using ENIQ to define the inspection case and critically design and study the inspection procedure (i.e. doing the input information and TJ), and using ASME as practical guidelines to required flaw populations etc. In fact, this approach is used as basis for grading in Finnish qualification guide documents [21]. It's still ENIQ, but with use of the know-how embedded in the ASME code. The disadvantage of using both ASME and ENIQ this way is, of course, that the cost of test blocks is higher than could be with ENIQ worst-case defects. On the other hand, extended practical trials provide increased confidence on the assessment done in the TJ. Table 1. compares the use of ENIQ and ASME.

Table 1. Comparison of ASME and ENIQ qualification

	ASME	ENIQ	ENIQ(+ASME)
Confidence provided	well-defined but limited performance	qualitatively-defined but possibly higher performance	possibly high performance with well-defined lower bound
Application	General and simple	Adaptive but complex	Adaptive and simple
Performance evaluated on	Various types of flaws in the test block	Expected or worst case defects in the case	Expected or worst case defects in the case
Cost	High cost of test blocks	High cost of TJ	High cost of TJ + High cost of test blocks

As for selecting optimal combination of 1G, 2G and 3G flaws, neither of the available guidelines help in (or even recognize) the choice between 2G and 3G flaws.

CASE STUDIES: LOVIISA QUALIFICATIONS AND FLAW SELECTION

In the following, three case studies of qualifications completed (or in progress) for the Loviisa power plant are presented. The Loviisa power plant is WWER-440 type PWR. The qualifications were done according to Finnish regulations [22], which closely follow the ENIQ methodology.

Fortum has constantly developed their qualifications and actively searched to improve qualification practices and representativeness of used test pieces. Also, there's been a number of qualifications completed and hence significant experience gathered during recent years.

For each case, the inspection target and input information is summarized; the considered flaw types and scope of inspection is documented. The input information considers three types of defects: specific defects, postulated defects and unspecified defects. The used test pieces and artificial flaws are described.

Specific defects are defects which the damage mechanisms of potential defects are well known and defects have been detected in the inspection objects in question or in the similar structures either at Loviisa unit 1 or 2 or in other VVER-440 units outside Finland.

The damage mechanisms of postulated defects are known and initiation and/or growing of the defects is assessed to be possible in the inspection object. Defect types have been observed in other locations in piping or components at Loviisa unit 1 or 2 or in other nuclear power plants (VVER, PWR, BWR), but not in the location to be inspected.

Unspecified defects are defect types which have not been detected, nor are they postulated in the inspection object, or damage mechanisms are not identified.

Due to confidentiality issues on the blind test pieces, not all the information can be published. The cases include use of different 1G, 2G and 3G flaw manufacturing techniques and to reveal their corresponding advantages. The decision on the used flaws is explained.

Case 1. Steam generator collector dissimilar metal weld (1G, 2G and 3G defects) (2007 - 2009)

Inspection of Steam Generator DMW is qualified for UT inspections. Inspection volumes are presented in Figure 2. The defect types specified in the input information are presented in Table 2. Detection target for personnel qualification in circumferential direction is 17 mm deep and 51 mm long defect and in axial direction 19 deep and 57 long defect. System detection target is 6x18mm for circumferential direction and in axial direction 7x21mm.

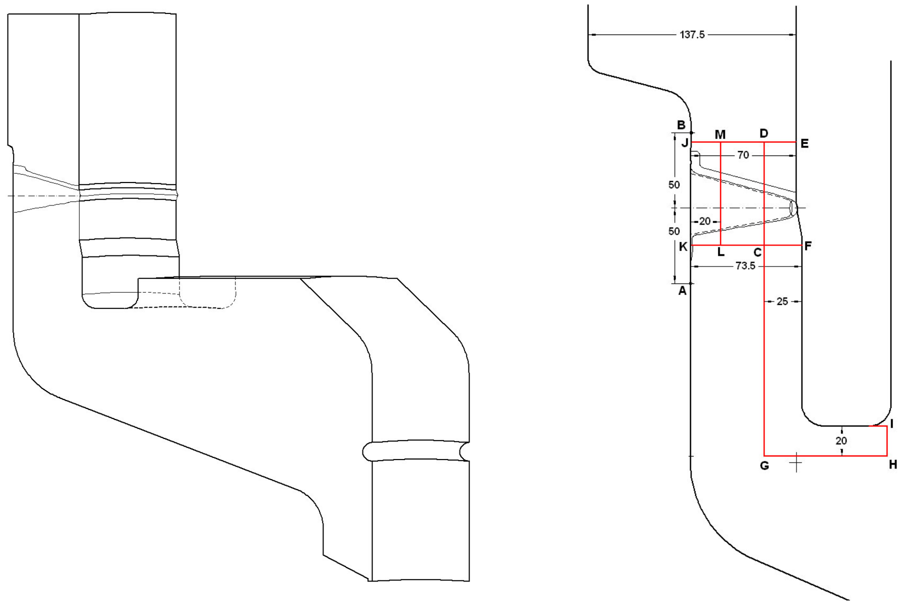

Figure 2. Steam generator collector dissimilar metal weld geometry and inspection target.

Table 2. Defect information for the steam generator DMW.

Defect type	Mechanism
Specific defects	Stress corrosion cracking, manufacturing defects (lack of fusion, slag lines, porosity)
Postulate defects	Stress corrosion cracking, Environmentally assisted fatigue cracking, Fatigue cracking
Unspecified defects	-

The test pieces use 1G, 2G and 3G defects. 1G -EDM notches are used because they can be easily and affordably produced to various locations and sizes. This allows manufacturing of wide variety of flaws that cover all potentially interesting configurations. Especially the configurations that are difficult for NDE, but not perhaps likely to occur in real inspection are studied with notches. They are also used in locations or configurations, where other flaw manufacturing technologies are not viable, e.g. due to manufacturing constraints or high cost. However, the notches are not considered representative to true in-service cracks defined in the input information and thus they are not considered sufficient alone.

2G defects (welded solidification cracks) were used in the dissimilar metal weld (DMW) region to produce deep cracks. These are affordable to produce and they provide better correspondence with the defined crack properties than EDM-notches. On the other hand, the weld material introduced causes differences in the NDE response (change in noise level etc.) which disturb the qualification. Also, the flaw types are still different from the types specified in the input information. Consequently, they were not considered to be sufficient alone. Also, the 2G flaws were considered inappropriate for the base material, due to disturbances caused by the weld material. Yet, it was decided that they provide good compromise between cost of manufacturing and flaw representativeness for the deep cracks.

3G defects (in-situ produced thermal fatigue cracks) were used in the base material locations and in the buffer-fusion line for smaller defects. The 3G cracks offer good representativeness with the defect types specified in the input information. They can be well used in the base material and other areas, where welding would disturb the qualification. On the other hand, the cost of production increases proportionately to the size of the flaws and thus they were not used for big flaw sizes. Also, some of the NDE-worst-case defects could not be readily produced (e.g., flaws with tilt). Consequently, the 3G cracks alone were not considered sufficient and they were used in concert with 1G and 2G flaws.

Case 2. RPV nozzle (1G, 2G and 3G defects) (2002 - 2010)

Inspection of inner corner area of Reactor pressure vessel nozzle is qualified for UT and ET inspections. Inspection volume is presented in Figure 3. The defect information from the input information is summarized in Table 3. Qualification of inspection contains near area inspections (30 mm from inside surface).

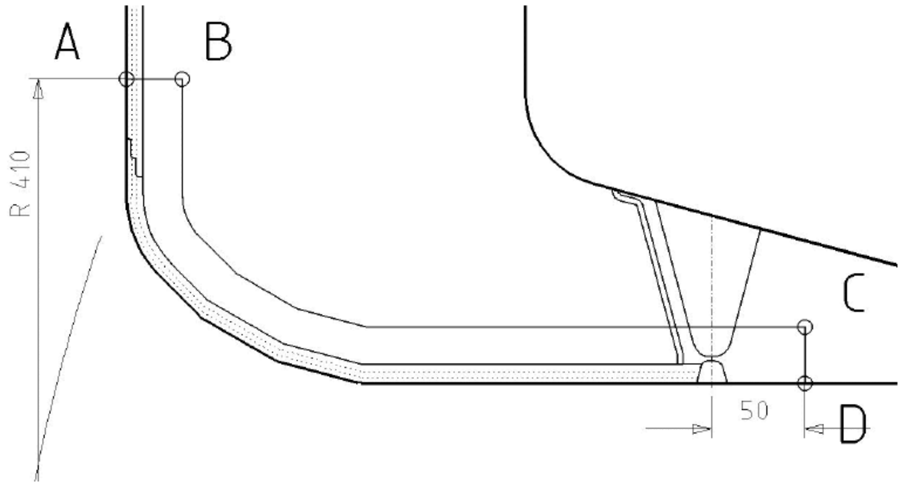

Figure 3. Inspection volume of RPV nozzle inner corner area. Inspection volume marked with A-B-C-D.

Table 3. Defect information for the RPV nozzle.

Defect type	Mechanism
Specific defects	Subsurface volumetric (slag, porosity) and planar (LOF) welding defects, solidification cracking.
Postulate defects	Fatigue cracks in nozzle inside radius, under-clad fatigue cracks
Unspecified defects	Transverse fatigue cracks

Slice of nozzle piece with width of 100 mm was used as open test piece in the first qualification trial in 2002. 1G EDM notches were used due to their ease of production: EDM flaws can be accurately produced, positioned, tilted, skewed and shaped. The notches are suitable for UT examination (often used as worst case reflector due to their specular reflection characteristics) and also for ET examination. However, the EDM notches were not considered to be representative for the defect types defined in the input information.

2G welded radial solidification cracks are used to simulate deep, open to surface and subsurface cracks for UT examination. One of the specific defect types in the input information was solidification cracking, so the flaw type offers good representativeness for these flaws. On the other hand, the extra weld material introduced in the process produces extra noise around the cracks, which disturbs UT. For ET, the welding disturbs strongly the examination of cracks and thus solidification cracks are not proper for qualifying ET examination.

Radial 3G thermal fatigue cracks were used for qualifying ET examination of cladding surface area where welding would have disturbed the qualification. For the shallow cracks needed for ET qualification, the production cost of 3G flaws was smaller than for the deeper cracks needed for UT. Also they are representative to the postulated defects

Case 3. Base material inspection, steam generator collector threaded hole (1G and 3G defects)

UT inspection with phased array technique was qualified for steam generator collector threaded hole. The defect types and scanning area is shown in Figure 4. The defect types from the input information are summarized in Table 4. Scanning is done from surfaces on the flange top and inner wall side.

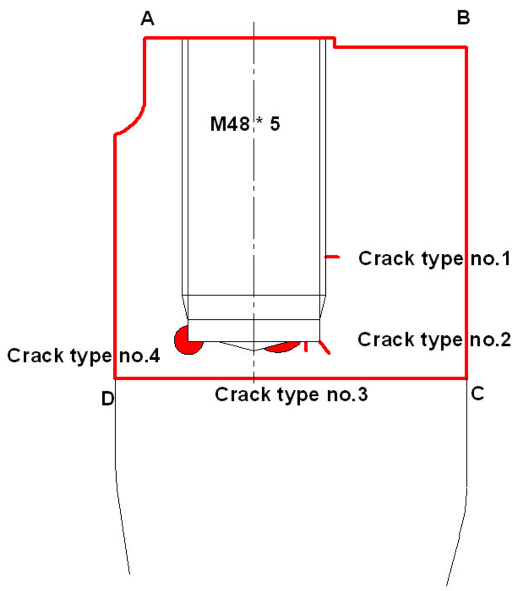

Figure 4. Inspection volume of threaded holes of steam collector flange area (marked A-B-C-D)

Table 4. Defect information for the steam generator collector threaded hole.

Defect type	Mechanism
Specific defects	Manufacturing defects (hot cracks, lack of fusion, slag inclusion)
Postulate defects	Fatigue cracks, Stress corrosion cracks
Unspecified defects	Thermal fatigue cracks

1G EDM notches were used, again, to cover wide variety of difficult to detect and/or difficult/costly to manufacture configurations such as very deep flaws and tilted flaws. Again, they were not considered sufficient alone due to lack of similarity to flaw types specified in the input information.

2G cracks were not used in this case. All the flaws are in base material and thus the weld material introduced by 2G methods were considered too disturbing to allow their use.

3G defects were used to get representativeness to the flaw types specified in the input information. Due to limitations in production time and cost constraints, 3G defects were not used for all locations.

DISCUSSION AND CONCLUSIONS

The above case studies demonstrate how the selection of different flaw types requires much expertise and experience beyond the guidelines given in ASME or ENIQ. On the other hand, quite clear and practical guidelines readily emerge from the practical case studies. These can be summarized as follows:

1G notches are best suited for studying range of different flaw configurations due to their ease of manufacturing and low cost. They can also be used to complement other flaw types in cases where production methodology limits possibilities. However, their response differs from real service-induced cracks found in service and thus they are not sufficient alone.

2G flaws are best used in cases, where they offer good compromise between producibility, representativeness and cost. They are more representative than the 1G flaws and offer significant cost advantage over 3G flaws in big flaw sizes. However, they are not suited to cases where the weld material introduced disturbs the inspection, e.g. in austenitic stainless steel base material UT (case 3) or in EC inspection (case 2).

3G cracks are important in cases where 2G cracks are not suitable due to weld disturbance. They offer better representativeness to real cracks but this advantage is weighted against cost of production. Since the cost of 3G cracks is proportional to crack size, they have been especially used in smaller crack sizes and /or smaller wall thicknesses.

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