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On welding residual stresses and their practical inclusion in structural integrity analyses

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1 ABSTRACT

This study concerns welding process induced residual stress distributions in Nuclear Power Plant (NPP) reactor circuit component welds. The covered weld residual stress (WRS) definition procedures are the ASME recommendations (Section XI Task Group, 1986, and Shack et al, 1983), the British Standard BS 7910: 1999 (British Standards, 1999), the R6 Method, Revision 4 (R6 Method, 2004), the SAQ handbook (Andersson et al., 1998), the SINTAP Procedure (SINTAP Final Procedure, 1999), the API 579 procedure (API 579 procedure, 2000) and the FITNET Procedure (Koçak et al., 2006). The covered WRS types are in as-welded state and after Post Weld Heat Treatment (PWHT). The examined weld types are circumferential NPP piping welds.

According to experimental measurements and the above mentioned seven procedures the WRS values are typically relatively high in NPP component welds which are in as-welded state. Thus it is of vital importance to take them into account in the structural integrity analyses, e.g. cracking sensitivity analyses. The WRS distributions present in a structure are the result of the manufacturing history and the elastic-plastic properties of the structure. The former referring to the mechanical and thermal processes executed during the whole production sequence and the latter to the elastic-plastic behaviour of the structure. After PWHT the WRSs are typically remarkably lower.

The WRS definitions in the mentioned procedures are based both on the available experimental data and Finite Element Method (FEM) analysis results. In some older ones of the mentioned WRS procedures, uniform distributions have conservatively been defined to WRSs for some cases due to lack of data, e.g. those given for parallel to weld for austenitic stainless steel for pipe-to-pipe welds in ASME recommendations.

2 INTRODUCTION

The published experimental WRS data have a substantial scatter. Consequently the defined WRS distributions have been developed as tensile upper bound solutions based on the data. However, according to (Bradford, 2000, Dong et al., 2000, Bouchard & Bradford, 2001, Dong & Brust, 2000, Dong et al.,1996), this approach not only lacks consistency for the same type of joints and welding parameters, but can either significantly overestimate the WRS level in some cases, or underestimate it in others.

Over the last decade or so, welding process induced residual stresses have received increasing attention in the pressure vessel and piping research community. The driving force for this interest can be attributed to the fact that application of modern structural integrity assessment procedures for defective welded components, e.g., the British Standard BS 7910: 1999, R6 Method, Revision 4, SINTAP Procedure, API 579 procedure and FITNET Procedure, require considerably more input data on the WRS state to give a more realistic assessment. The conventional approach for characterising a WRS profile has been to adopt a tensile upper bound solution, as mentioned above. All WRS procedures covered here base their definitions on material yield strength, so that typically the maximum absolute WRS values are nearly at yield strength, usually acting at weld inner and outer surfaces. The variation of the yield stress values within the typical operational temperature range in Light Water Reactor (LWR) NPP piping systems, being approximately from 20 to 330 °C, is of the scale of 10 %. For austenitic NPP piping stainless steels (SSs) the stress values at 1.0 % strain should most often be used for yield strength, whereas for corresponding ferritic SSs the stress values at 0.2 % strain should be used, respectively. The input data needed in using the WRS definitions in the above mentioned seven procedures are presented in Table 1 in the following.

The examined seven WRS procedures provide a range of approaches to define the WRS distributions. In older WRS procedures, such as ASME recommendations, only one approach in the form of a few simple functions is given, whereas in more recent WRS procedures, such as R6 Method Rev. 4, several levels for defining WRSs are presented, ranging from coarse level 1 definitions giving single values, to level 2 with WRS definitions as analytical functions, to subtle and computationally laborious level 3 approaches, requiring e.g. the use of advanced non-linear 3D FEM analysis tools. Depending on the needed accuracy and available resources, one can choose which WRS procedure to apply. In general, the WRS distributions are defined in all of the examined seven procedures also (or only) with analytic functions, such as polynomials and exponent function. On the behalf of the more recent WRS procedures, these correspond to level 2 definitions. Separate definitions are typically given for austenitic and ferritic SS materials, weld types and weld wall thickness ranges. Also, overall validity ranges are given in most procedures for WRS definitions, as a function of e.g. weld wall thickness and yield strength.

One unfortunate departure from realism in case of some of the more recent WRS procedures, e.g. R6 Method Rev. 4 and FITNET, is that in the transverse to weld direction the WRSs are not self-balancing. While making local crack growth calculations with a fracture mechanics based analysis tool this feature may not pose remarkable problems, but in case of corresponding 3D FEM analyses it is quite the other way around, as in order to achieve equilibrium FEM automatically modifies the WRSs towards self-balanced distributions over the component model walls, and thus the original WRS distributions are not maintained.

Table 1. For circumferential welds in austenitic and ferritic SSs NPP piping components, a summary of required input data concerning the examined seven WRS distribution procedures (Cronvall, 2008). Notation "X" means that the input data parameter in question is required for the procedure in question.

Parameter	**Physical Dimension**	**Weld Residual Stress Procedure**						
		ASME recommendations	**BS 7910: 1999**	**R6 Method, Rev. 4**	**SQA Handbook**	**SINTAP procedure**	**API 579 procedure**	**FITNET procedure**
Geometry input data parameters								
Wall thickness	mm	X	X	X	X	X	X	X
Outer radius	mm		X			X	X	
depth of repair weld	mm		X	X		X	X	X
Material strength input data parameters								
Stress at inner surface	N/mm^2	X						
Weld metal yield stress	N/mm^2		X	X	X	X		X
Parent metal yield stress	N/mm^2		X	X	X	X	X	X
Welding process input data parameters								
Electrical energy per unit length of weld	J/mm		X					
Electrical heat input	kJ/mm			X				X
Welding process efficiency				X				X
Weld arc power	J/s			X		X		X
Weld travel speed	mm/s			X		X		X
Radius of the yield zone for a thin plate	mm			X				X
Radius of the yield zone for a thick plate	mm			X				X
Welding current	A			X				X
Welding voltage	V			X				X
Coefficient of thermal expansion				X				X
Young's modulus of material	N/mm^2			X				X
Density of material	kg/mm^3			X				X
Specific heat of material	J/kg°C			X				X

3 APPLICATION OF WELD RESIDUAL STRESS DEFINITION PROCEDURES

3.1 Analysis input data and scope

In this study the WRS distributions are calculated with the above mentioned seven procedures for representative small, medium and large NPP reactor circuit pipe cross-sections in Finnish Boiling Water Reactor (BWR) NPP units. The dimensions of these pipes are:

- Small pipe; outer diameter = 60 mm, wall thickness = 4.0 mm
- Medium pipe; outer diameter = 170 mm, wall thickness = 11.0 mm
- Large pipe; outer diameter = 510 mm, wall thickness = 26.0 mm

For these three pipe sizes WRS distributions through wall are calculated for austenitic SSs in both perpendicular and parallel to weld directions. The covered weld conditions in the calculations are as-welded state and after PWHT.

The temperature is set to 286 °C in all calculations, corresponding to operational temperature in Finnish BWR NPP units. In this temperature the stress at 0.2 % strain of the considered austenitic SS is 125 MPa. Of the covered WRS procedures, those in BS 7910: 1999 and API 579 consider the stress at this strain for austenitic SS as the yield strength, whereas according to R6 Method, Rev 4, SAQ handbook, SINTAP and FITNET, the yield strength for these materials is taken to correspond the stress at 1.0 % strain, respectively. Here 1.5 times the stress at 0.2 % strain, i.e. 187.5 MPa, was taken to correspond the stress at 1.0 % strain for austenitic SS, as according to (Andersson et al., 1998). As for WRS procedure in the ASME recommendations, the yield strength is simply taken as 30 ksi (207 MPa) in all temperatures, corresponding on average to the room temperature yield strength of the SS weld test specimens used to provide part of the associated WRS data (Rudland et al., 2008). The tensile strength of the considered austenitic SS is 383 MPa. In the calculations here, the value of the Young’s modulus in the considered temperature is 176 GPa, and the value of the Poisson’s coefficient is 0.3, respectively.

3.2 Summary of WRS application results

For the examined NPP pipe weld cross-sections the WRS distributions through wall and perpendicular to weld in as-welded state differ quite much from each other both in shape and by their values. Near and in the inner surface the WRS values vary approximately between 50 to 300 MPa of tension, where the highest values are given by the SAQ handbook procedure. Near and in the outer pipe surface these values differ more, reaching also compression, there the maximum value being approximately -200 MPa, and given by the ASME recommendations and SINTAP procedure. Many times the WRS distributions exceed the above mentioned yield strength value by approximately from 10 to 60 %. However, the tensile strength is not exceeded so realism is not violated. As worldwide more than 90 % of the primary circuit piping crack cases have been oriented parallel to weld (i.e. circumferentially), see e.g. (Brickstad, 1999), it is these axial WRSs perpendicular to weld that play a prominent role in piping crack growth. For Small and Medium pipe weld cross-sections most of the perpendicular to weld WRSs are linear, whereas for Large pipe weld cross-section they are mostly non-linear. Self-balancing WRS distributions are mainly given by ASME, SAQ and SINTAP procedures, whereas other procedures give mainly or only out-of-balance distributions. Procedures in R6 Method Rev. 4 and FITNET give here identical WRS distributions, as the WRS definitions from the former procedure have been copied as such to the latter and more recently published procedure. An example of the WRS calculation results is presented in the following Fig. 1. Part of the result curves in Fig. 1 were taken from the main background document here (Cronvall, 2008), which is more a parametric examination for comparison of several characteristics concerning the above mentioned WRS definition procedures, and the rest were calculated within this study.

For the examined NPP pipe weld cross-sections the WRS distributions through wall and parallel to weld in as-welded state are quite similar, varying approximately between 100 to 200 MPa of tension, and barely changing as a function of the wall thickness. The only exception here is API 579 procedure, as it gives linearly altering distributions with on average 200 MPa of tension in the inner surface and on average 50 MPa of tension in the outer surface, respectively. The SAQ procedure gives the highest WRS values for all analysed pipe sizes. At maximum the applied procedures give WRS values exceeding the yield strength by approximately 10 %. Thus none of them exceeds the tensile strength. The WRSs parallel to weld are important e.g. in such respect that axially oriented cracks have been detected from RPV nozzle welds, and stresses oriented perpendicular to faces of such cracks promote/increase their growth. Also, the stresses caused by system pressure are in general twice as high in the circumferential i.e. parallel to weld direction, than in the axial i.e. transverse direction, thus adding to the growth rate of possible axially oriented crack like flaws.

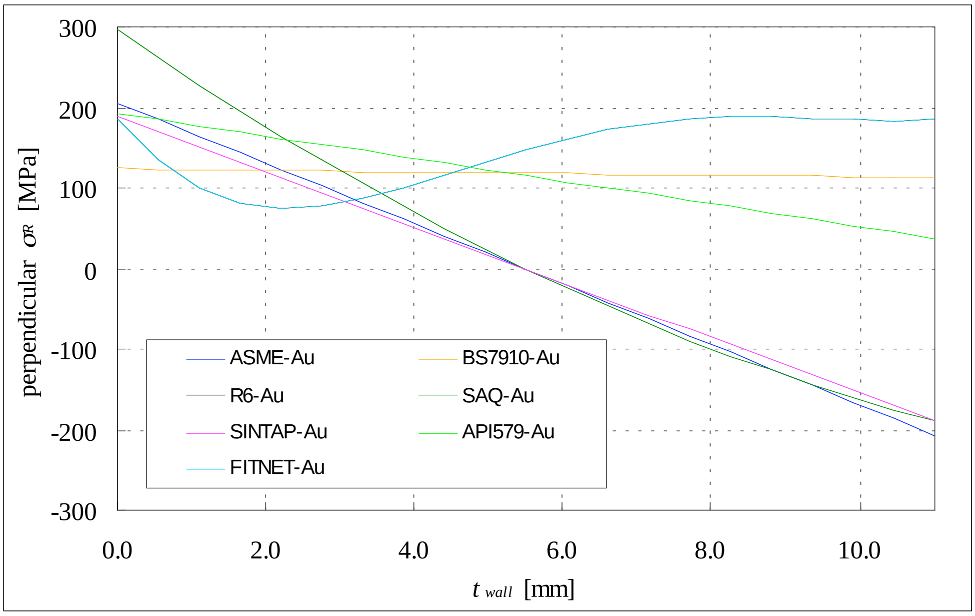

Figure 1. WRS distributions through wall and perpendicular to weld in as-welded state for the pipe with cross-section Medium, for its dimensions see Section 3.1, calculated with the seven examined WRS procedures. Here in case of FITNET, R6 Method Rev. 4, BS 7910: 1999 and API 579 procedures, low heat input was conservatively selected. Here x is a radial coordinate through pipe wall with origin on the inner weld surface, and in the legend "-Au" in the end of procedure name means that the curve in question is for austenitic SS.

As for WRS distributions perpendicular and parallel to weld after PWHT, they vary between 20 to 30 % of the considered yield stress for the examined pipe weld cross-sections. Thus according to the examined WRS procedures the PWHT considerably relieves the WRSs in welds as compared to those in the as-welded state, respectively.

The differences between the recommended WRS distributions through wall and perpendicular to weld in as-welded state stem from several reasons, mainly relating to the available measured WRS data and/or FEM analysis result data, based on which they have been defined, and procedure scope concerning e.g. geometry, material and weld procedure parameters. The WRSs depend on complex interacting factors, which are difficult to simulate consistently using solely FEM. Defining reliable WRS distributions from measurements is also problematic because of the complex local and global spatial distributions of stress, the innate variability of WRS fields (even in welds fabricated to identical procedures) and because of the limitations of the measurement techniques themselves. If more numerical and measured data are indiscriminately accumulated, it seems inevitable that an upper bound approach will tend to give a profile approaching uniform yield magnitude. It so appears that some of the WRS distributions through wall and perpendicular to weld in as-welded state are somewhat erroneous and could give misleading, sometimes non-conservative, fracture assessment results. The more recent procedures are, however, backed by more measured residual stress data and more accurate FEM analysis result data, so for the assessment of the NPP piping WRS distributions through wall and perpendicular to weld in as-welded state these procedures are recommended, i.e. API 579, SINTAP, R6 Method Rev. 4 and FITNET, even though their match is not so good in some cases. These more recent procedures are also recommended for the assessment of WRSs in all other directions and for all other weld types and treatments. Of these four procedures the API 579 appears to give the most conservative WRS distributions for piping welds, whereas BS 7910: 1999 appears to give the least conservative WRS values.

In the light of the WRS analysis results here only ASME recommendations and SINTAP procedure in all cases, and SAQ handbook in most cases, give WRS distributions that are self-balancing in the transverse to weld direction. Of them the least over conservative WRS procedure appears to be SINTAP.

4 FRACTURE MECHANICS BASED CRACK GROWTH ANALYSES CONSIDERING WRS DISTRIBUTIONS

4.1 Analysed degradation mechanism, associated analysis input data and used analysis tool

The examined NPP pipe weld cross-sections here are the same as in Chapter 3, namely; Small pipe, Medium pipe and Large pipe, for details see Section 3.1. The examined load case is static operational conditions.

The examined degradation mechanism in all crack growth analyses is Stress Corrosion Cracking (SCC), which is a localised non-ductile progressive failure mechanism that occurs only in case the following three conditions are fulfilled simultaneously, see (European Commission, 2001):

1. The stress around the crack tip is tensile.
2. The environment is aggressive.
3. The material is susceptible to SCC.

When these conditions are met, the intergranular SCC failure mode, IGSCC, is considered in the associated analyses.

SCC is a delayed failure process. That is, cracks initiate and propagate at a slow rate until the stresses in the remaining ligament of metal exceed the fracture strength. The sequence of events involved in the SCC process is, according to (Jones, 1992), usually divided into three stages:

1. Crack initiation.
2. Steady state crack propagation.
3. Final failure.

The fracture mechanics based crack growth rate equation used in the analyses, which depicts intermediate (stage 2) SCC, is according to (Congleton, 1982):

$$\frac{da}{dt} = C \cdot K_I^n \tag{1}$$

where a [mm] is crack depth, t [year] is time, K_I [MPa√m] is mode I stress intensity factor, and C and n are constants characterising the material properties as a function of temperature and environment. The values of these constants and a summary of other needed input data are given in Table 2. In the SCC analyses the stress distributions caused by static process loads, here mainly system pressure, were added by superposition to the corresponding WRS distributions, respectively. No K_I threshold value was considered in the SCC analyses. The aspect ratio of the analysed crack postulate, i.e. crack depth divided by its length, was kept as constant through each crack growth analysis.

Table 2. Summary of the input data needed in the SCC analyses of the three considered circumferential piping welds. When three values are given, they are presented in the order; Small pipe, Medium pipe and Large pipe. Considered load case; static operational conditions.

Dimension & Material Property Data		**Loads & Stress Data**	
Pipe dimensions [mm]	see Sect. 3.1	Pressure [MPa]	7.0
Material strength values [MPa]	see Sect. 3.1	Temperature [°C]	see Sect. 3.1
Young's modulus [GPa]	see Sect. 3.1	Axial stress due to pressure [MPa]	22.8, 23.5, 30.8
Fracture toughness [MPa√m]	350	Circumferential stress due to pressure [MPa]	45.5, 47.1, 61.7
Initial crack depth & length [mm]	0.1 & 0.6		
SCC rate equation parameters;		Used WRSs according to; ASME, BS 7910: 1999, R6 method Rev. 4, SAQ handbook, SINTAP, API 579, FITNET	
C [(mm/year)/((MPa√m)^n)]	1.42E-04		
n [-]	3.0		

The fracture mechanics based crack growth analyses were performed with the analysis code VTTBESIT. This analysis code comprises parts developed by the Fraunhofer-Institut für Werkstoffmechanik (IWM), Germany and by VTT.

With VTTBESIT it is possible to calculate stress intensity factor values in several points along the crack postulate fronts, including deepest point (crack tip) and edge/end points. The analysis code treats only the mode I loading in which the direction of the loading is perpendicular to the crack surface (crack opening mode), and the analysis procedure is linear-elastic. These calculations are carried out with program BESIT60, developed by IWM. This program is based on the weight/influence function method. Solutions are provided for "infinite" and semi-elliptical surface crack postulates in straight plates and cylinders. The theoretical background and analysis procedures of BESIT60 are presented in references (Varfolomeyev, 1996, Busch et al., 1994, Busch et al., 1995).

VTTBESIT uses the BESIT60 program code as a pure stress intensity factor value computing subroutine and applies the results as starting values for crack growth assessments. Two crack growth models are provided in the analysis code: Paris-Erdogan equation for fatigue induced crack growth, and rate equation for SCC, here equation (1) (Vepsä, 2004).

4.2 Summary of crack growth analysis results

Two examples of the fracture mechanics based SCC analysis results are presented in the following Figs. 2 and 3. Part of the result curves in these result Figs. were taken from the main background document here (Cronvall, 2008), which is more a parametric examination for comparison of several characteristics concerning the above mentioned WRS definition procedures, and the rest were calculated within this study. In Figs. 2 and 3 the same notations and coordinate system are used as in Fig. 1 in Section 3.2.

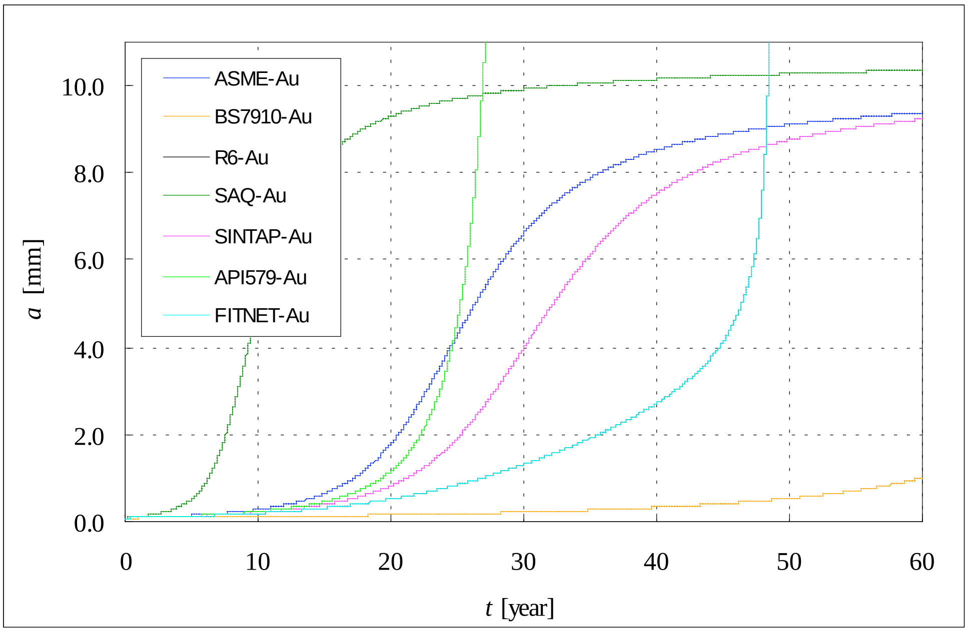

Figure 2. For semi-elliptic inner circumferential surface crack postulate under axial stresses the crack growth histories through weld wall in the Medium pipe, for which the axial WRS components for as-welded state are presented in Fig. 1, and the considered degradation mechanism and time span are SCC and 60 years, respectively.

The simulated crack growth rates for semi-elliptic inner circumferential surface crack postulate through weld in as-welded state differ quite much from each other. This is especially so for those three procedures which give the highest tensile WRSs through wall, namely the ASME recommendations, R6 Method Rev. 4, FITNET procedure and API 579 procedure. Of these four procedures API 579 gives the highest tensile WRSs near the inner surface, causing the considered crack postulate to grow more rapidly through weld than in case of any of the other considered procedures.

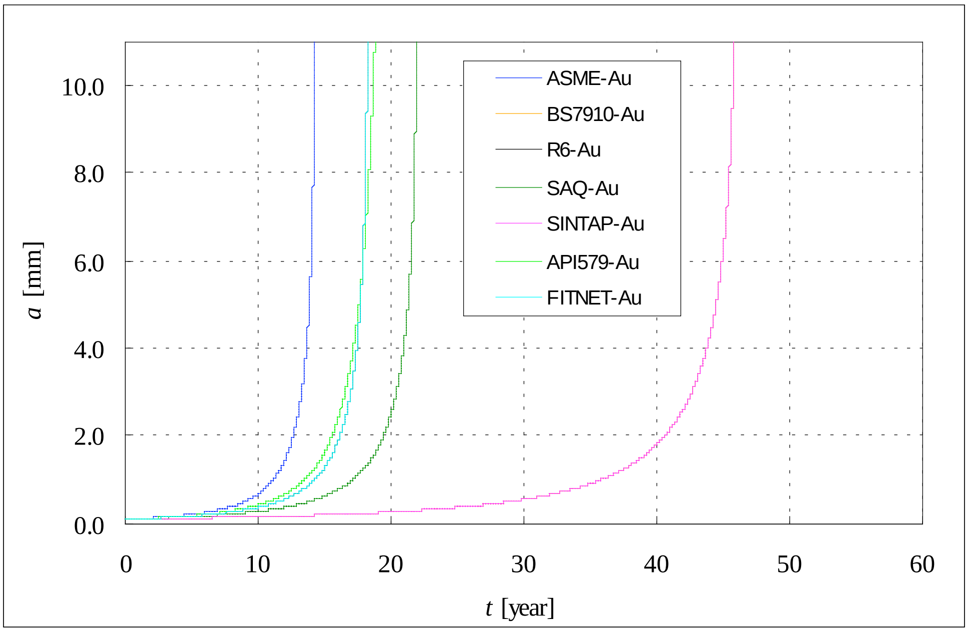

Figure 3. For semi-elliptic inner axial surface crack postulate under circumferential stresses the crack growth histories through weld wall in the Medium pipe, for its dimensions see Section 3.1, for which the corresponding circumferential WRS components for as-welded state are considered, and the considered degradation mechanism and time span are SCC and 60 years, respectively.

As for the crack growth rates for semi-elliptic inner axial surface crack postulate through weld in as-welded state, they are similar in the sense that in all cases the crack sooner or later grows quite quickly through the wall. The ASME recommendations, R6 Method Rev. 4, FITNET procedure and API 579 procedure give the highest tensile WRSs through wall in circumferential direction, and consequently in those cases the quickest crack growth ensues. However, for the Large pipe with the circumferential WRSs according to the ASME recommendations the slowest crack growth results. This is due to ASME recommendations giving the lowest tensile WRSs in and near the outer weld surface. In general the axial crack postulate grows faster than the corresponding circumferential one, which is due to tensile WRSs being in general higher in the circumferential direction through weld than in the axial. Also, the stresses caused by the operational system pressure are in general twice as high in the circumferential direction than in the axial, as mentioned earlier.

As for the crack growth rates for semi-elliptic inner circumferential surface crack postulate through weld which has been in PWHT, they are almost identical in that crack growth is practically insignificant. The same result holds also for the corresponding semi-elliptic inner axial surface crack postulate through weld which has been in PWHT. These results are obviously caused by the low WRSs as defined in the considered procedures for a weld which has been in PWHT, being of the scale between 20 to 30 % of the material yield stress. In the light of the analysis results, PWHT appears to remarkably decrease the growth rate of the piping weld cracks.

According to results from a set of fracture mechanics based crack growth analyses performed to the above mentioned three pipe welds, the compared crack growth rates show both discrepancies and similarities. According to analysis results the quickest crack growth through wall for circumferential crack postulate in weld in as-welded state was approximately 27 years, in case of the Small pipe and the API 579 procedure, and for corresponding axial crack postulate approximately 12 years, again in case of the Small pipe and this time the ASME recommendations, respectively. For the crack growth rates through wall in weld after PWHT the analysis results matched with each other for the covered procedures either quite or very well. In the light of the analysis results PWHT appears to remarkably decrease the growth rates of the piping weld cracks as compared to those for welds in as-welded state.

5 CONCLUSIONS

The more recent WRS procedures are backed by more measured data and more accurate FEM analysis result data than the corresponding older ones. So for the assessment of the WRS distributions through wall and perpendicular to weld in as-welded state these procedures are recommended, i.e. API 579, SINTAP, R6 Method Rev. 4 and FITNET, even though their match is not so good in some cases. These more recent procedures are also recommended for the assessment of WRSs in all other directions and for all other weld types and treatments.

However, the more recent WRS procedures are also more complex to apply than the older ones, as the equations are both longer and more numerous. Also, considerably more input data are needed, and if measured data are not available, somewhat conservative assessments and/or standard/handbook values have to be used.

When looking from the viewpoint of avoiding excess conservatism in structural integrity analyses, it is recommended to use such a more recent procedure that gives the lowest WRSs for the analysed weld in question. Possibly this requires making the crack growth analyses using several of the more recent WRS procedures, as it is not necessarily in advance obvious with which of them the slowest crack growth will be achieved. This is because in addition to the magnitude of the WRS values, also the shape of the stress distribution affects the crack growth in the analyses.

One unfortunate departure from realism in case of some of the more recent WRS procedures, e.g. R6 Method Rev. 4 and FITNET, is that in the transverse to weld direction the WRSs are not self-balancing. While making local crack growth calculations with a fracture mechanics based analysis tool this feature may not pose remarkable problems, but in case of corresponding 3D FEM analyses it is quite the other way around, as in order to achieve equilibrium FEM automatically modifies the WRSs towards self-balanced distributions over the component model walls, and thus the original WRS distributions are not maintained. Thus for FEM analyses the use of SINTAP procedure and ASME recommendations, which in all cases appear to give self-balancing WRS distributions over weld, are recommended, respectively. The less over conservative of these two procedures appears to be SINTAP.

One interesting subject of further research would be to simulate with a suitable FEM analysis code how the WRSs alter over the years in plant operation (e.g. to see if and how much they decrease), due to various typical/expected yearly transient load cases. When having such stress results, it could also be examined what is their impact to the corresponding simulated crack growth rates. Especially when a NPP has been in operation for some decades, it could be assumed that the WRSs have relieved at least to some extent due to typical repeated mechanical loads. On the other hand, the operational temperature of BWR units is too low for stress relieve caused by creep to take place.

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