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Fracture Mechanics and Structural Integrity

EC FP7 Structural Performance of MULTI-METAL: Ambitions, results, implications and discussion

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ABSTRACT

The purpose of this paper is to present a part of the results achieved within the MULTIMETAL project, its conclusion and recommendations, and proposal for further investigation. Focus is on the structural integrity assessment of dissimilar metal weld (DMW). The EURATOM supported project started in February 2012 and ended in 2015. The project is coordinated by VTT with 10 partner organizations from Europe: AREVA (SAS & GmbH), CEA, JRC, EdF-Energy, BZF, EDF, TECNATOM, JSI, and Studsvik Nuclear AB. The aim of the project was to develop a standard for measuring the fracture resistance of multi-metallic specimen and development of harmonized procedures for dissimilar metal welds (DMWs) ductile integrity assessment.

DMWs connect ferritic and austenitic stainless steels and are present in a number of primary piping systems in light water reactors. They contain a number of different material zones, i.e. ferritic zone, austenitic zone, weld material and heat affected zones which differ significantly in their material properties and fracture behaviour.

The project ambitions, results and implications are generally presented and discussed. The main work was focused on testing the three mock-ups containing DMWs resembling real DMWs from NPPs in terms of geometry, material and weld procedure. The material test program involved tests with standard geometry specimens (CT, SENB, SENT) which were cut from the mock-ups. Numerical calculations were performed utilising State-of-the-Art on integrity methods for DMW. The project also includes both experimental and numerical benchmarking and preparation of best practice documents.

INTRODUCTION

Dissimilar metal welds (DMWs), such as joint welds between ferritic steels with either austenitic stainless steels or Nickel-base alloys, are commonly found in piping systems of nuclear power plants (NPPs) as well as in other industrial plants. Depending upon the specific application these welds are usually produced using either austenitic stainless steel filler materials (electrodes) or nickel-base filler materials, manual or automatic welding process, V grooved or Narrow gap. Due to the large number of manufacturers and applied optimization methods existing DMW configurations are numerous.

In recent years some concerns have been raised about the reliability of DMWs, especially when the plant in focus is in operation beyond its initial design life. Integrity assessment of flaws in welds requires substantial material data like fracture toughness values, which are evaluated according to standards that are not necessarily foreseen for the weld configuration in focus. There is thus a need to develop a standard for toughness measurements in multi-metallic specimens. In addition harmonised procedures for defect assessment in DMWs would be advantageous. In this context the MULTIMETAL project was aimed at delivery a good practical approach for testing, integrity and LBB analyses.

The project had seven WPs. WP1 was dedicated to coordination (VTT). In WP2, relevant information from field experience on design, manufacturing issues, integrity assessment codification and material characterization are selected for DMWs in primary circuit piping systems of nuclear power plants. Four plate mock ups (one narrow gap Alloy 52 weld mock-up, two stainless steel weld mock-ups, one VVER-type weld mock-up) were prepared and extensive characterizations (tensile, hardness, EBSD, residual stress, fracture toughness using different specimens (C(T), SEN(B) and SEN(T)) are performed in parallel at different labs, following a detailed matrix. This was done in WP3 and it is the core of the project. To support the experimental work, numerical efforts including state of the art of the integrity assessment of DMWs (specimen and components) was performed in WP4 which includes finite element codes ABAQUS, ASTER, Cast3M, SYSTUS, ANSYS, and MARC. Recommendations on testing and on numerical assessment were benchmarked in WP5. European researches on DMW components were summarized and a best practice was issued, including recommendation gained along the project (WP6). Finally in WP7training and dissemination of the knowledge were done following the defined scheme.

The main results of the project will be presented for each WP and detailed presentations are given in parent paper at the SMIRT conference.

WP1 Project Management

In addition to management and coordination, WP1 included the creation of a website hosted by TECNATOM, dedicated to the MULTIMETAL project participants.

WP2 State of the art and collection of field experience

In a first part data on the design variant of plant components, their degradations and reported crack issues from open field cases were collected. The different designs are

1. Buttering and final joint welds consists of stainless steel welding (mainly used in United States (US) and France, and for old PWRs and BWRs in Germany.
2. Buttering and final joint weld consist of Ni based alloy (mainly used in US and in Germany for PWR's, however the root of the weld can be made of austenitic steel in Germany)
3. First buttering layer consists of Stainless-steel with increased Ni-content; further buttering and butt weld is done with Stainless-steel welding material (mainly used in Russia)
4. Narrow gap weld consist of Ni based alloy, mainly used for modern nuclear power plants (NPPs).

Welding process was manual for existing running plants. For newest plants, automatic welding process is given preference. Only ductile fracture is relevant for such DMWs. Recommendations on crack locations for fracture toughness specimens cut from a DMW narrow gap mock-up were made based on experiences:

• Lowest tearing resistance (J-R) is at the fusion line. The crack deviates to the lowest strength area driven by the strength mismatch. It is possible that the crack grows into a region which does not have the lowest intrinsic fracture toughness. Proposition for notch locations: at fusion line (ferritic / Inconel), +0.5mm (in the Inconel weld metal) and -0.5 mm (in the ferritic HAZ) from fusion line.

• The weakest area for ductile failure mode is the area with a plasticity/damage concentration i.e. high stress triaxiality (ratio of hydrostatic stress / equivalent stress), therefore the notch location is set to the fusion line (ferritic steel/Inconel), and to 0.5mm and 1mm from FL (in the Inconel weld).

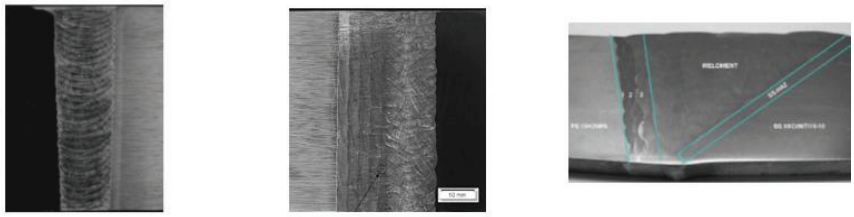
Information was gathered on the effect of residual stress fields due to welding on fracture testing procedure: after specimen cutting residual stress is reduced. However cracks can be deviated during pre-fatiguing at low K-level. The tearing resistance of tough joints seem not to be affected by residual stresses at usual LWRs service temperatures. Defect assessment codified procedure overview for DMW shows

that a detailed guidance is given in the R6-code [R6] (three level assessment: engineering assessment method up to numerical approach). Acceptance criteria for defect in DMW region can be obtained from evaluation mainly based on modified limit load assessment according to ASME XI and KTA 3206 which is also dealing with break exclusion assessment. A two-level assessment has been proposed by C. Faidy starting with limit load evaluation for tough DMW with a tearing resistance larger than 100kJ/m², based on European research programs dedicated to assessment of flaw in large piping DMWs (stainless steel variant) within BIMET and ADIMEW projects. Validation of LBB for the DMW narrow gap Ni based variant has been done within STYLE project. The DMW variant with Ni-based buttering for German plant (small piping DMW DN80 and DN300) has been investigated at MPA. Actual experimental mechanical and fracture toughness procedures have been compiled leading to a list of main open points concerning DMWs issues and a recommendation for preparing specimens in WP3.

Tensile properties investigation needs to distinguish between several DMW regions. The specimen preparation for toughness tests is a challenging task. Normally the weld interface is not perpendicular to the pipe outer surface. Thus, several steps are needed to guarantee a correct cutting. Placing a crack at the interface is challenging due to the irregular shape of the interface. Fracture testing based on ASTM E1820 procedure J is preferred for CT and SEN(B) specimen to obtain engineering fracture toughness. There is no consensus concerning the use of the given eta and gamma factor as well as on the correctness of the compliance formula or the validity limit. Therefore verification using numerical methods is needed. Appropriate post-test fractographic and metallographic investigation is of utmost importance in order to identify the particular microstructures actually sampled by the propagating crack. A theoretical open gap remains, i.e. the validity domain of J which is given at least up to initiation, but which can be challenged in the case of large plasticity, like for tough DMW. For plastic materials (large hardening coefficient n), the singularity of the HRR field disappears and the deformation concentrates along a single slip line emanating from the crack tip, see Joyce (2012).

WP3 Experiment design and guidelines

Robust procedure for fracture resistance measurement of DMWs was the main aim of the project. Four plates covering three DMW design variants have been manufactured see Figure 1. MU1 was a narrow gap Alloy 52 weld without buttering, the base materials were made of ferritic pressure vessel steel 18MND5 (SA 533) and the stainless steel AISI 316L. For MU2a and b, the same base materials as MU1 were used but the weld was composed of an austenitic stainless steel and has a V-shape weld, the first two layers buttering was 309L followed by four layer and weld 308L. Base material of MU3 was a pressure vessel steel 15H2MFA (cut from original VVER 440 reactor sample, from Paks Nuclear Power Plant) and a stainless steel X6CrNiTi18-10 (1.4541) (similar to 08H18N10T). PWHT has been performed for all MUs. MU2 was used during the benchmark. Hardness measurements showed a hardened zone in the austenitic HAZ adjacent to the welded zone for MU1. The highest hardness was obtained in the ferritic HAZ. Two types of specimens were used in the MULTIMETAL Project: tensile specimens dedicated to identify the mechanical behaviour of the various materials constituting the DMW and fracture toughness specimens aimed to measure the ductile tearing resistance of the DMW.



Material	MU-1	MU-2	MU-3
Samples no.	1 & 2	4	3
Ferritic part	18MND5 (SA 533)	18MND5 (SA 533)	15H2MFA
Backing bar	UNS N06600 (Inconel 600)	316L	n/a
Filler wire	INCONEL 52	308L	316L
Buttering	None	309L+308L	EA395/9+EA400/10T
Austenitic part	X2CrNiMo17/12 (316 L)	X2CrNiMo17/12 (316 L)	X6CrNiTi18-10 (321)

Figure 1. Mock ups of DMWs for the MULTIMETAL project

The microstructure and intragranular misorientation was measured using the electron backscatter diffraction EBSD technique in a scanning electron microscope. Apart from gaining more knowledge about the microstructure of the different mock-ups the strain distributions showed a gradual strain increase towards the fusion border on the austenitic side. A similar trend was observed on the ferritic side. However, a very steep increase in the strain was observed on the ferritic side the last 100 μm to the fusion border. This localized strain increase was not detected on the austenitic side. Residual stresses were measured using the diffraction technique at the Petten research reactor for MU2 and MU3. Tensile tests providing a complete profile of the specimen could be obtained using the CEA solution based on laser sensors and combined with numerical simulations using Cast3M code. See Figure 2 (top) for CEA setup for MU1 using a cross weld specimen (normal to the welding direction, T tensile axis). The local stress-strain behaviour of material could also be obtained considering miniature tensile specimens using a set-up consisting of camera LED lightening and the Aramis software, as it was performed at VTT for MU1 Figure 2 (bottom) and MU3. Engineering stress strain curves were obtained from displacement gauge data and true stress-strain curve were constructed based on optical measurements. For MU3, tests on 2 mm width flat tensile specimens were performed at BZF at 300°C and at room temperatures. Engineering and true stress strain curves have been determined.

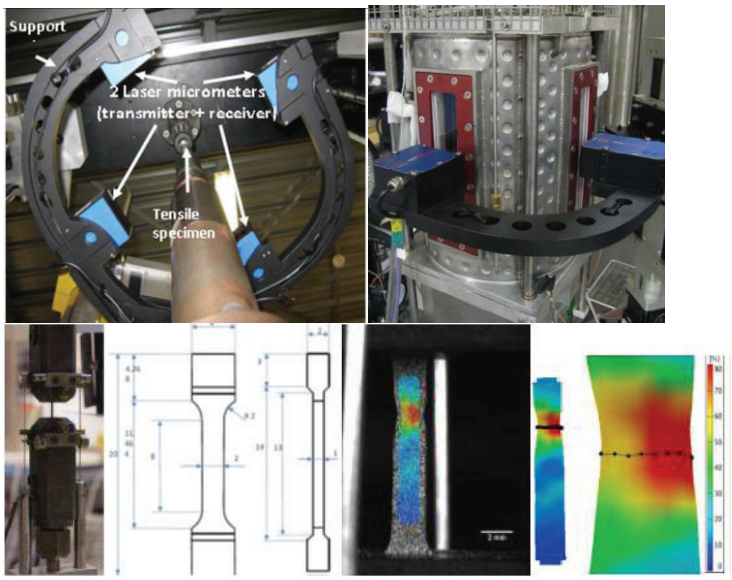


Figure 2. CEA patent pending diameter measuring system (top), local true-stress for MU1 using advanced measurement ARAMIS method at VTT (bottom)

A strength peak was measured (BZF and VTT) at ferritic 15H2MF/weld metal fusion line at room temperature for MU3. In the ferritic HAZ 2 mm away from the fusion line, low yield strength was obtained: different types of microstructural zones developed during manufacturing of the weld.

The strength behaviour of the two mock-ups has few similarities: in both welds the ferritic base metal has a higher strength than the weld metal; the peak strength is in the LAS/weld metal interface region. The measurements on strength behaviour are relevant in interpretation of crack growth behaviour. The crack growth paths are controlled by the strength properties. In numerical assessments of multi-metal welds, the true stress-true strain curves are needed.

Three types of fracture specimens were investigated: the compact tensile (CT) specimen, the single edge notch bending (SENB) specimen, and the single edge notch tensile (SENT) specimen. The two first specimens are fully specified in the ASTM E 1820 Standard and in the ISO 12135 Standard. In contrast, presently no standard is available for the SENT specimen, only best practices (DNV and Exxon).

The cutting of specimens with crack planes located at the fusion line is a difficult task and needs several steps of cutting. At each step it is necessary to be able to define the location of the fusion line plane or what is considered to be the fusion line with sufficient accuracy (because in reality there is not a straight interface between the two materials).Firstly mechanical polishing and etching of the weld lower side of MU1 has been done and it was necessary to machine two reference sides. A test matrix for MU1 has been created: the fracture toughness was determined using CT12.5 (AREVA, CEA) and CT25 (CEA) as well as SE(B) specimens (VTT) with dimensions (thickness x width x length) of 10 mm x 20 mm x 100 mm, side grooved after pre-fatiguing 20%. Fracture resistance curves, J-R curves, were determined at room temperature for near interface zones of the Inconel 52 DMW mock up; a) fusion line between the ferritic steel 18MND5 and Inconel 52 (AREVA, CEA, VTT), b) heat affected zone (HAZ) at a distance of 0.5 mm from fusion line on the ferritic steel 18MND5 side (CEA, VTT) and c) Inconel 52 weld metal at a distance of > 0.5 mm from the fusion line (AREVA, CEA, VTT). For MU3, non-side grooved 10x20 SE(B) specimens have been tested at RT and 300°C, for each temperature 6 specimens in bulk material, 9 specimens in weld and 3 specimens in HAZ. In the case of SEN(T) specimen the clamped specimen was preferred compared to the pin loaded configuration in order to limit the rotation and to avoid parasite bending moment and pin gripping. ΔK value around 20 MPa$\sqrt{m}$ was preferred to achieve the desired a/W. The participant achieved this task successfully with an average distance to the FL within the height of the fusion line wavy plane. Slight deviation of the crack from the fusion line into the ferritic HAZ has been noticed for some specimen during pre-fatiguing. 20% thickness side grooves can be introduced to facilitate pre-fatiguing and to avoid crack deviation.

For ductile tearing fracture test, the ASTM1820 methodology was given preference. Crack growth was followed by recording CTOD clip gage measurement as well as potential drop detection (CEA, to get insight of crack initiation). After tearing, a heat treatment at elevated temperature (400°C 1h) tinted the crack faces.

Based on the results it can be concluded that ductile tearing occurred in all fracture toughness tests. The fracture toughness was high in all investigated regions. Fracture paths were determined with a detailed topography of fracture surfaces and cross-sections. Investigations at AREVA on CT12.5 with a notch located near or at fusion line revealed many secondary cracks perpendicular to the main fracture surface. The zones of fracture revealed a transgranular dimple fracture. The crack did not jump to the fusion line if the distance to the fusion line was greater than 0.5 mm. Large plastic deformation after tearing could be easily seen for all types of specimens. The austenitic alloy 52 exhibited much higher necking compared to the ferritic side. A slip line could be seen on CT12.5 and CT25 specimens with crack at FL, underlining

that ductile tearing and plastic collapse may compete even for large specimens. Tearing initiation occurred very frequently at a load close to the limit load.

Identical J-R curves (valid J_Q) were obtained at CEA and AREVA (FL crack) even though the specimen orientation was different. The crack extension was not correctly evaluated using ASTM1820 compliance for tests performed on CT25 at CEA because a negative extension at the beginning of the test could be calculated, which is not in line with the physical propagation, and a correction should be applied. VTT results from SE(B) for MU1 were in line with the CT25 results, but none of the six specimens were found to be valid according to ASTM1820-13 criteria: larger specimens would be required.

For SE(B) a bending correction for the compliance must be applied otherwise crack growth is underestimated. In the case where the crack was located in the 18MND5 HAZ at about 0.5 mm from fusion line, the crack turned to follow the fusion line suggesting the weakest toughness region is the wavy fusion line. A profilometer has been used on SE(B) and CT12.5 specimens to investigate crack propagation on a global scale. For VVER type mock-up materials fracture tests were performed using 10x20 SE(B) specimens (without side-groove) at room temperature and +300 °C. The buttering layers have the lowest fracture toughness at both temperatures, $J_Q \approx 100$ kJ/m² was obtained at +300°C. The design of tearing tests was based on the current standard for homogeneous material (ASTM E1820), but the interpretation of the test (load displacement) is more complex and a connection with numerical analyses is needed for validation. Precise location of the zone with smallest fracture toughness cannot be defined. The location of lowest fracture is dependent on the specimen.

Residual stress measurements by neutron diffraction have been undertaken at the Joint Research Centre in Petten, NL. Sections of Mock-ups 2 and 3 were made available for these measurements. Later comparison with complementary data from additional measurements, but also from predictions, is still envisaged in order to achieve a more detailed assessment of these results.

WP4 Numerical analysis of DMW behaviour

The outcomes of the numerical fracture analyses performed within the European projects ADIMEW, NESC VI, BIMET and NULIFE pilot study on DMWs were summarised. Additionally the in-house methods developed by nuclear organisations were presented. A collection of methods described in scientific literature were referenced. Classical FE analysis was performed for J integral estimation in CT, SEN(B) and SEN(T) specimens. A robust validation began with investigation on homogeneous specimen, in a second step non-homogeneous specimen were assessed. Comparison between the calculated eta factors (η_{pl}) and analytical ones according to ASTM E1820-13 or DNV were performed. Despite of different model setups (symmetry/no symmetry, application of loads, usage or not of special crack tip elements with embedded strain singularity and mesh densities), the scatter in the obtained results is relatively low. The load-line displacement curve needs to be computed with sufficient resolution and the original loading slope needs to be estimated reliably because the computed plastic area under the load curve (A_{pl})can have a significant impact on the computed η_{pl}.

Comparisons between 2D (plane strain) and 3D have been made on all specimen types. A good agreement for CT specimen considering 2D plane strain, the converging η_{pl} is similar within 10% to the ASTM1820 values considering an a/W from 0.5 to 0.7. The benchmark exercise also showed that the number of covered cases was too high and emphasised the need for accurate prescription of boundary conditions, geometries and corresponding meshing. One of the covered cases with significant differences in calculated results between participants will be reviewed within Numerical Benchmarking in WP5. Another type of numerical simulation has been considered. Local approach analysis were based on numerical simulation of MU1 (welding, machining, PWHT) and were performed for several specimens taken from this mock-up (CT and SENT specimens). Accuracy has been investigated by various

measurements such as the hardness, the local stress-strain curves, and the elastoplastic predictions of the load-displacement curves of the fracture specimens without damage. Residual stresses were released after PWHT and machining in the plate as well as after cutting of the specimen.

WP5 Benchmark (experimental and numerical work)

All types of specimens have been investigated during experimental benchmark using MU2 and the recommendation for fracture resistance measurement from WP3. The recommendations from WP4 were applied for the numerical benchmark. The benchmark includes experimental and numerical work based on a test matrix, which was defined during the project. The results of the different participants of the benchmark exercise in WP4.2 showed significant deviations for certain cases. As a consequence the partners involved were asked to review their analysis results for a specific Mock-up 1 SENB case and repeat the corresponding analyses for a two dimensional (2D) and three dimensional (3D) case. The contributors to the WP5.2 benchmark exercise were asked to compute η_{pl} from both LLD and CMOD. The computed η_{pl} - factors were compared with analytical solutions given in ASTM1820-13 for a homogeneous specimen of the same dimensions. In general, good agreement amongst participants was obtained for the 2D cases.

WP6 Lessons learned and Best practice documents

Feedback from MULTIMETAL and previous projects (STYLE ADIMEW, BIMET) has been summarized. A key issue is the tensile behaviour determination for the DMW. Recommended testing is based on CT specimens, since most of ASTM1820 can be considered in that case. The characterization of ductile tearing of a crack located at the interface between the filler metal and the HAZ of the ferritic steel is considered to be the weakest link in term of crack resistance. The notch was located within 0.1 mm from the FL. For the VVER design variant, the first buttering layer is also of interest. The mismatch (M) is the ratio between the yield strength of the filler metal and the base metal. M is less than 1 when considering the couple weld metal – ferritic HAZ in a DMW. The η_{pl} function is affected by M. The real η_{pl} function (as retrieved from FEA) is higher than the conventional value provided by the standards for M below to 1. It is necessary to either determine a suitable compendium or to re-calculate the η_{pl} function (as well as γ function) by the finite element method if a more accurate value is needed. The modelling must consider the appropriate behaviour laws of all materials. The compliance solution given in ASTM 1820-13 underestimates the crack growth in the specimen during tearing for testing with SEN(B) specimens. The residual stresses are generally erased by the plasticity which appears in the specimen due to the important ductility of the materials. Therefore the eventual residual stresses do not impact the final result. The construction of the blunting line has a direct impact on the fracture property $J_{0.2}$ and depends on the adopted S_y value. At the interface, the validity of the blunting line must be discussed. The limit load of non-homogeneous specimens is still under discussion as well as criteria on toughness level to assure crack initiation over a predefined plastic limit load.

WP7 Young scientist exchange and training

Transfer of knowledge to younger generations is one of the objectives followed by the global nuclear community. An exchange program and a training course based on outcomes and experiences gained from MULTIMETAL have been performed for young scientists. BZF hosted the training course which included lectures and laboratory experiments. Knowledge preservation of the project is supported by the learning materials produced for the training course.

DISCUSSION

The toughness concept and the parameter $J_{0.2}$ remains relevant for DMW. Large plastic deformation occurs in the specimen, and plastic strain is not confined any more (see Figure 6) at the crack tip but develops into the material with lower yield level for increasing load. Slip line seen during experimental testing underlines that large plastic deformation located in the weakest material occurs in the non-homogeneous undermatched specimen. Ductile tearing and plastic collapse can compete. Wasylyk has investigated similar plastic deformations during ductile tearing testing of austenitic steel (316L) and tearing initiation was occurring after achieving the limit load for this tough material. In the investigation made in the 1980's (see Golembiewski) and lately in 2005 (see Chen), limit load (scaled on the yield strength) was reached for various types of metals while undergoing significant crack extension by intending to perform J-R curves. For tough steels, it could be seen as a plastic tearing problem in opposition to a "fracture" problem governed by singularity parameters and the slow-stable-ductile crack extension is driven that case by tensile material properties.

CONCLUSION

All DMW design variants show a high resistance to crack growth under the condition of investigation. Experimental testing was supported through numerical investigation. The practical approach/ best practice /guideline found in MULTIMETAL consist of:

- The most critical zone for DMW in terms of fracture lies in a narrow band around the weld-Low Alloy Steel interface
- Local tensile properties are a key issue for analyzing the toughness tests.

For the test realization, it is advised to follow the recommendation of the usual standards (ASTM E1820 or ISO 12135). Specific attention should be paid to the fatigue pre-cracking to get straight crack propagation

- For the DWM characterization use of CT specimen is recommended. It is in general acceptable to use the standard ASTM 1820 η_{pl} function but it may lead to an underestimation of the toughness initiation value for 0.5T specimen. It is not possible to provide a general trend on the suitable eta function compared to the standards solution
- Location of the crack must be at the fusion line (+/-0 mm) between ferritic heat affected zone and Ni-base alloy for Ni-based narrow gap DMW
- The size of the specimen required to assess fracture toughness must be checked since plastic collapse can occur in too small specimen.
- The residual stresses are in general erased by the plasticity which appears in the specimen and therefore they do not impact the final result of tearing initiation
- For testing using SEN(B) specimen, the compliance solution given in ASTM E1820 underestimates the crack growth in the specimen during tearing, rotation correction should be applied
- 3D numerical assessment is needed for verification of eta and gamma for configuration which were not investigated during the project
- For tough DMW components (Ni-variant with Ni-based alloy) the integrity assessment can be limited in a penalizing way to a limit load analysis. It is recommended to use existing codification ASME XI, KTA 3206, R6.

Further work is needed to assess the validity of the J-concept for tough material (J_{limit}), as well as the transferability from specimen to larger component. The validity of the blunting line should be investigated as well. SEN(T) specimen are promising due to a constraint level more similar to the condition of welds in piping, however the numerical assessment show large scatter which was not expected, and this should be investigated in details.

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NOMENCLATURE

CT	Compact tension
CTOD	Crack Tip Opening Displacement
CMOD	Crack mouth opening displacement
EBSD	Electron backscatter diffraction
ESIS	European Structural Integrity Society
EU/EC	European Union / Commission
DMW	Dissimilar Metal Weld
DNV	Det Norske Veritas
FE	Finite Element
HAZ	Heat Affected Zone
HRR	Hutchinson, Rice and Rosengren
J_{el}	elastic part of the J-integral
J_{pl}	plastic part of the J-integral
J-R	J-integral versus crack growth resistance
$J_{0.2}$	Engineering initiation toughness
KWU	KraftWerk-Union
LA	Local Approach
LAS	Low alloy steel
LBB	Leak-Before-Break
LLD	Load line displacement
LWR	Light Water Reactors
NPP	Nuclear Power Plant
SEN(B/T)	Single-Edge-Notch Bend/Tension
Sy	Effective yield strength
WP	Work Package
FL	Fusion Line
LAS	Low Alloy Steel
CS	Carbon steel
M	Mismatch
RT	Room Temperature
a	Crack depth
B	Specimen thickness
B_N	Net tthickness
b_0	$W - a_0$ original crack size

W	Width = 2xB
η_{pl}	eta factor
A_{pl}	plastic area under the load curve

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