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FRACTURE PROPERTIES IN DISSIMILAR METAL WELD JUNCTIONS: METHODOLOGY OF CHARACTERIZATION

Myriam Bourgeois[1], Yann Kayser[1], Gregory Perez[1], Olivier Ancelet[1],

Päivi Karjalainen-Roikonen[2], Stephane Chapuliot[3].

1 CEA, DEN, DM2S, SEMT, LISN, 91191 Gif-sur-Yvette, FR
2 VTT Technical Research Centre, FI
3 AREVA NP, 1 Place Jean Millier, 92400 Courbevoie, FR

ABSTRACT

Within the framework of European project MULTIMETAL (Structural performance of multi-metal component), several fracture tests on different types of multi-material specimens have been performed. Present fracture toughness standard methods, e.g. ASTM 1820 are not directly intended for Dissimilar Metal Weld (DMW). Therefore further investigations are needed in order to define the best practice in fracture mechanical tests and their analysis for DMWs.

Specimens are taken from welded plates: a narrow gap Inconel DMW junction between Ferritic and Austenitic steels, designed and delivered by AREVA France. The elasto-plastic laws of behaviour for each constitutive material of the DMW junction are presented. Several location of crack has been chosen in the vicinity of the weakest area in terms of fracture resistance: interface Inconel/FS. The aim of the project is to provide guidelines for the DMW mechanical properties. Several normalized specimens - geometries like CT, SENB or SENT specimens - have been machined in the DMW junction. The determination of fracture toughness in ductile tearing regime has been studied. J_Q has been determined for all specimens according ASTM 1820 or DNV standards. The values are very high and very sensitive to the choice of blunting line. The DMW is particularly high resistant in front of ductile tearing: the more the crack is far from the fusion line interface, the more the ductile tearing is difficult.

This paper highlights the difficulty to transfer the fracture properties from one type specimen to another (size effect, geometry effect, loading conditions…). The specimen's deformations are unsymmetrical. The next step is FE analysis of each specimen to understand and reproduce the plastic constraint effect, and the identification of the most important differences with the standards when working on heterogeneous specimen.

INTRODUCTION

FP7 MULTIMETAL project is a European project launched in 2012 [MULTIMET, 2012] on the specific question of fracture characterization of weld joints. Nuclear Power Plants contain a large number of welded structures and welds represent their weakest part with respect to fracture probability. In welded joints the risk of defects is larger; the material toughness is in most cases lower compared to the base metal. Additionally, in the example of DMW, many questions arise due to the presence of an interface between two different materials.

The overall aim of this project is to develop pre-standard guidelines for the measurement of DMW material properties and to develop a good practice approach for the fracture assessment of DMWs. Presently no common standards are available for materials testing of DMWs. For that purpose, relevant tests matrix has been defined on three dedicated Mock-ups with DMWs. Combining FE analysis and experimental results, the fracture tests can be reinterpreted and the validity of standard discussed.

DMW MOCK-UP DESCRIPTION

The mock-up, namely MU1, is an inconel 52 narrow gap tig weld between the stainless Steel 316L and the 18 MND 5 Ferritic Steel. The MU1 provided by AREVA-NP France has a thickness of 62mm. Plates rather than pipes have been chosen in order to simplify the cutting into specimens and to allow a study on a large range of geometries.

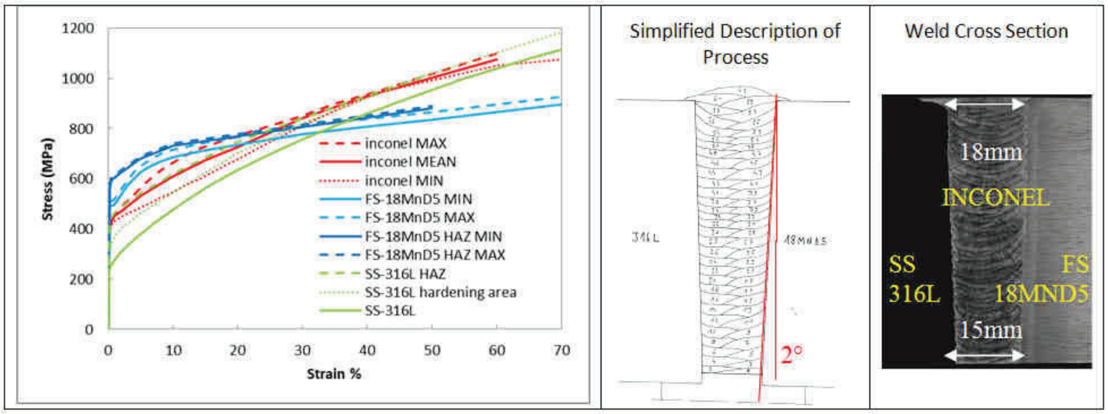


Figure 1: MULTIMETAL MU1 provided by AREVA-NP.

The macrograph of the weld cross section reveals the several beads during welding process and also the HAZ of the FS (Figure 1). A Post Weld Heat Treatment PWHT has been carried out at 595-620°C during 3 hours. On the macrograph of the welded junction, it can be seen that the thickness of the weld is varying between 18mm to 15mm, which denotes a sidewall angle about 2°. This angle is in accordance with the slope machined before welding on each side of the two dissimilar plates and shrinkage during the welding process.

To characterize the properties of a junction, hardness measurements have been performed and specific cross-weld smooth tensile specimens have been performed to identify the gradient of properties in the junction. As seen Figure 1, the junction is in overmatch condition on FS side: the yield stress is higher in FS than in Inconel zone, and the junction is in under-match condition on SS side: the yield stress is lower in hardening SS than in Inconel zone. The multi-material tensile test revealed a hardening area in SS material and the HAZ in FS close Inconel interfaces. A dedicated tensile device, equipped with laser sensors, has been developed at CEA and was used on the specific cross-weld specimen for this study. This device namely IMEC® is able to provide a wide-ranging profile of the specimen during the tensile test. Details of this study can be found in [Bourgeois, Ancelet et al.] (2015).

The overmatch between Inconel and HAZ of FS is quite important. Past studies [STYLE 2010, ADIMEW 2006] have shown that the weakest area in terms of toughness is at fusion line between Inconel/FS (HAZ) that is why the ductile resistance of DMWs should be study in the vicinity of this interface.

DEFINITION OF THE TESTS MATRIX IN MULTIMETAL PROJECT

For the fracture test task, the tests matrix has been defined in order to cover different topics:

- Size effect: CT25 and CT12.5
- Geometry effect: SENT, SENB

- Crack plane orientation: representative of surface crack (SC) or through wall crack (TWC) propagation
- Distance of the crack plane to the Inconel/FS interface plane

The final test matrix for the fracture task on MU1 is presented in Table 1, three partners were involved ANP-G, VTT and CEA. This paper will focus on tests: CT25, CT12.5, SENT22 and SENB10x20.
The methodology is detailed for the example of CT. Then results are summarised and discussed for each type of specimen.

Table 1: Tests matrix relative to MULTIMETAL.

propagation **Partner**	SC **ANP_G**			TWC **CEA**							SC **VTT**					
Specimen	CT12.5			CT25			CT12.5		SENT 22x22		SENB 10x20			SENB 10x10		
Nb	2	2	2	2	2	2	2	2	2	2	2	2	2	4	5	5
ID				745A-A							FL	FL -0.5	FL 0.5			
				I, J	K, L	M, N	Q, R	S, T	U, V	W, X	A, B	A, B	A, B			
Crack plane location	FL	INCO		FL	INCO		FL	FS	FL	INCO	FL	INCO	FS	FL	INCO	FS
Distance from fusion line		0.5	1		0.3	0.5		0.5		0.3		0.5	0.5		0.5	0.5

METHODOLOGIE OF FRACTURE TESTS

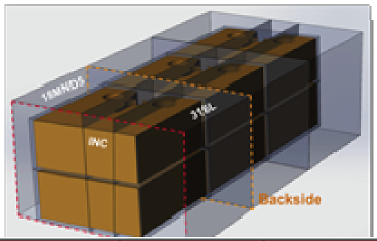
Preparation of fracture test specimen

Cutting specimen with crack plane located at a fusion line is a difficult task and needs several steps of cutting and at each step to be able to define with sufficient accuracy where the fusion line plane is, and what is considered for the fusion line (because the reality is not a straight interface between the two materials). At each step of the machining, the location of interfaces is revealed and their positions measured on each side of block. The specimens were machined with the chosen crack plane position at a precise distance front the interface FS/Inconel.

On drawing of block cutting (Figure 2) we can see that two specimens are sampled in the thickness of the mock-up. That means the thickness of the weld is not the same in the two specimens, due to the angle of welding, and the properties can differ from one to another CT25 due to the effect of gradient of properties in the weld. Specimen machining and crack plane positioning results is given for all the CT25. Side groves have been machined before pre-crack step (10%SG) and after for the ductile tearing test (20%SG). These groves allow keeping in place the crack propagation in a plane and obtain a straight front.

Experimental Procedure

Significant attention has to be paid to the fatigue pre-cracking phase in order to avoid any crack deviation from the original crack plane. This deviation can be induced by residual stresses and/or the mismatch of the different materials generating a mixed mode loading condition. The machining of side grooves prior to the fatigue pre-cracking is in general a good solution to avoid any crack deviation. The choice of a sufficient high value of ΔK is a supplementary precaution to reduce the residual stress effect and wavy front crack. For example, the pre-crack were performed on CT25 from 0.4 to 0.5 a/W under constant ΔK of 22MPa.m$^{1/2}$ and specimen were flipped at half pre-cracking. For all the specimens CT25 listed in Table 1, the fatigue has been performed with a machined crack at a/W=0.4 until a/W=0.5, that means from 20mm to 25mm. Even though the crack propagation was carried out on a large extension (2mm is sufficient in general) the crack front remained approximately linear. No effect of residual stresses has been detected.



CT25 Specimen Name	Expected distance in INC mm	Average distance in INC mm
745A-AH	0	0,04
745A-AI		0,00
745A-AJ	0,3	0,31
745A-AK		0,26
745A-AL	0,5	0,39
745A-AM		0,47

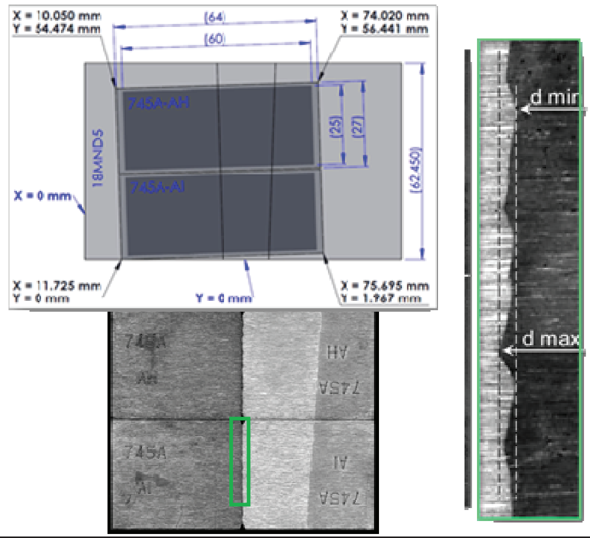


Figure 2: Positioning of the interface with associated drawings for CT25 specimens and measured distance between virtual crack plane and interface for the six specimens.

745A-AI	745A-AM	745A-AI	745A-AJ

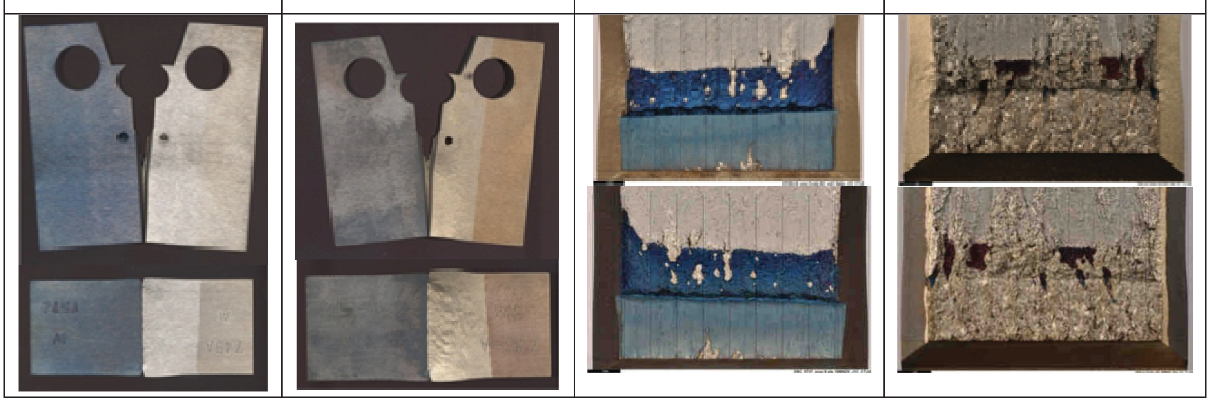


Figure 3: Example of CT25 deformations and fracture surfaces both sides FS or SS: comparison between crack propagations of 4mm in fusion line mostly in FS (AI), and of 2mm mainly in Inconel (AJ).

The testing were carried out according standard ASTM E-1820-08a test method, [ASTM, 2008], on fracture specimens using Single-Specimen Unloading Compliance method. The crack length was calculated from the specimen compliance at unloading points in course of the tests. PDD measurement (Potentiel Drop Detection) was added to get more information of initiation and crack propagation. After ductile tearing tests, specimens were heat treated at 400°C during 1h. Fatigue post-crack test were done until complete failure. The “9 points” procedure was used to measure initial crack length (end of fatigue pre-crack) and final crack length after ductile tearing.

After the heat treatment, FS has been colored in blue (Figure 3). The deformation in Inconel is larger when the crack was located near fusion line in Inconel side, than when located at fusion line. After heat treatment and post-cracking test, the fracture surface can be observed for the both sides: Inconel and SS steel part or FS part. A necking is observed on the side of the most ductile material, that is why the measurement with the “9 points” has been done mainly on the part in FS.

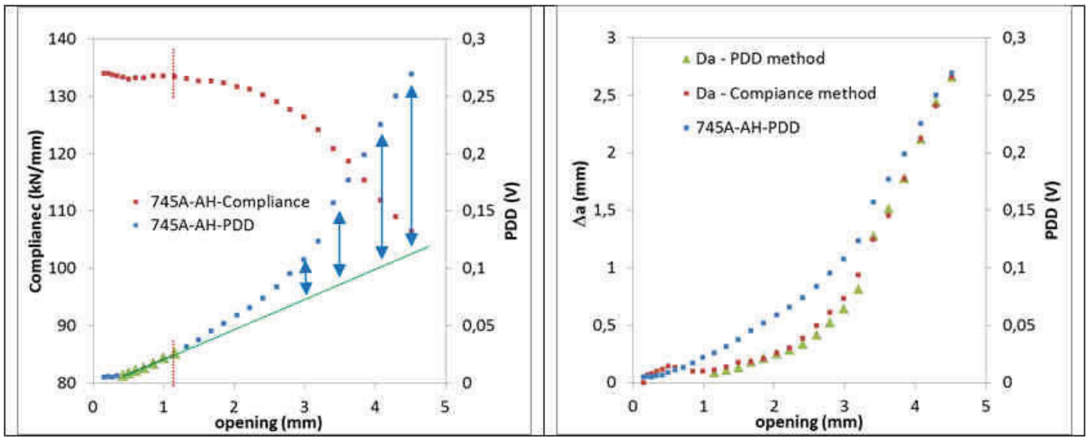


Figure 4: Determination of crack growth: compliance and DDP methods applied on a CT25.

An example of test records, load versus COD clip on gage is plotted Figure 4. The PDD measurement gives an indication of the initiation of ductile propagation. The changes of slope of the curve, PPD versus clip gage, correspond to changes in term of geometry of the specimen, due to the crack propagation and also due to plastic deformation. Assuming the first part until red dotted line is due to plastic deformation, the difference between the PDD and green line values is the part due to ductile crack propagation. A relation can be established: the ratio of current crack and final crack length equals the ratio between the linearly equation Δ_{PDD} versus CMOD taken respectively at current point and final point. The Δ_a values calculated from compliance method and PDD method are very similar in the case of CT specimens (Figure 4). Concerning the SENT, the PPD evolutions versus CMOD are difficult to be interpreted, especially when crack is in Inconel side. Several phenomenon of plasticity in different material and change of geometry (due to plasticity deformation near grip) make it sometimes impossible to be related to crack propagation. The evolutions of crack opening are different than those obtained with compliance method on SENT (see § on SENT analysis, Figure 9).

Another instrumentation have been used on CT12.5 specimen: a camera system takes pictures of the crack in the notch at each unloading step. The distance between the two lips of the initial fatigue pre-crack is increasing until establishment of a blunting phenomenon (plastic deformation at the tip of the crack) and then the crack initiation occurs (Figure 5). The ductile propagation reached 2mm at the end of this test. Despite the fact that this is a surface observation, (not exactly the same propagation in the bulk of the specimen), those pictures at each unloading step give successful information of the initiation.

Conducted on another CT12.5 specimen, this time with a crack put in the FS side at 0.5mm, the initiation is detected at a similar value than the previous test, the crack at the end of the fatigue pre-cracking step is probably the same, despite the fact that the machined V tip was not located at the same place at the beginning of fatigue crack growth. After that point, the load versus CMOD curves are not similar, the ductile crack growth occurs and then a deviation is observed. The fracture surfaces observed post-mortem demonstrate clearly the deviation of the crack until it reaches the wavy fusion line interface for the second specimen (dark color is FS, yellow is Inconel).

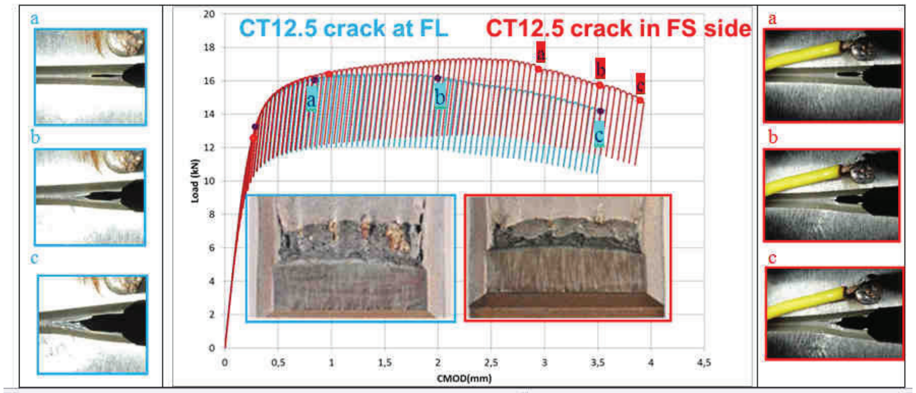


Figure 5: Load versus CMOD, CT12.5: comparison of crack location, Specimens AQ and AT.

According to ASTM E-1820 standard, the JR curve can be evaluated with the Single Specimen Unloading Compliance method. The crack length was calculated from the specimen compliance at unloading points in course of the tests. $C_{c(i)}$ being the load-line crack opening elastic compliance at each sequence, the crack length a_i, normalized by W, can be estimated by using the equation (1). The function f is in the ASTM standard for CT and SENB, and found in literature for SENT, see Tyson (2014):

$$u = \frac{1}{\left[B_e \; E \, C_{c(i)}\right]^{1/2} + 1} \qquad with \quad \left(\frac{a}{W}\right)_i = f(u) \tag{1}$$

J values can be calculated by using the curve load versus plastic opening displacement as follow:

$$J = \frac{\left(1-\upsilon^2\right)K^2}{E} + J_{pl} \quad \text{with } \; K = \frac{P}{\sqrt{BB_N W}} f\left(\frac{a}{W}\right) \tag{2}$$

$$J_{pl} = \frac{\eta\left(\frac{b}{W}\right)\times A_{pl}}{B\times b} \quad \text{with } \; \eta = 2 + 0.522\left(\frac{b}{W}\right) \; \text{ and } \; \gamma = \eta - 1 - \left(1 - \frac{a}{W}\right)\frac{\eta'}{\eta} \tag{3}$$

The *eta* and *gamma* functions (given here for CT specimen) are valid for homogeneous specimen. In a first approximation, all the results presented here used the standard recommendations to evaluate the JR curve. The formulae needed for the calculation of K and eta have been taken in the DNV standard (2006) for the SENT specimen. After having measured the initial crack and the final crack length, the (J, Δa) curve have been corrected. The two methodologies of measuring crack growth give the same results on that example 745A_AH (Figure 6).

In the case of multi-materials CT and SENT specimens, the choice has been done to take Inconel properties for the construction line. All CT25 and SENT22 specimens have revealed a strange phenomenon of decreasing crack length when applying compliance method. This phenomenon is illustrated on Figure 7. All the curves have then been corrected by a shift on the crack extension axis. The compliance method gives unphysical values of a.

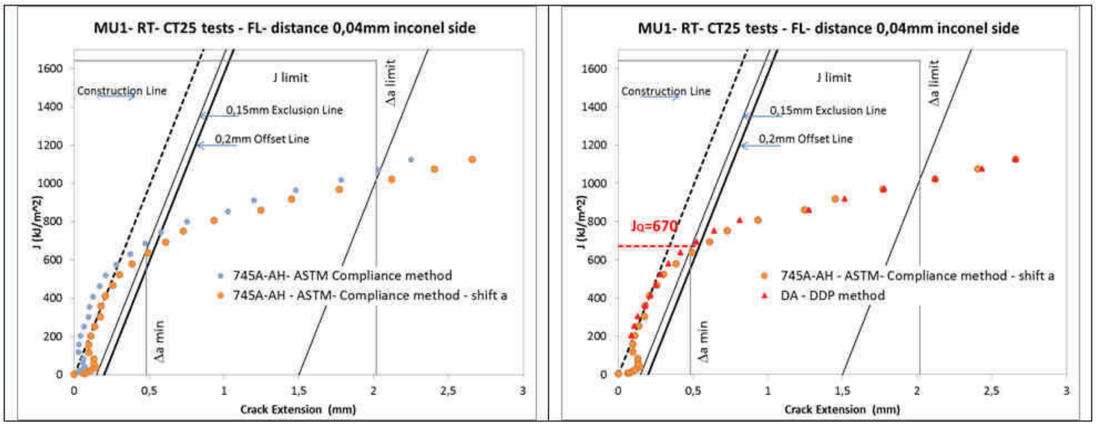


Figure 6: J-R curve, crack in Inconel for CT25 (AH), corrected curve with physical crack value, comparison with crack growth obtained by the PDD measurement, (slope σy = (385+600)/2, M=4).

The reason for this can be the high levels of plastic deformation in the area of the crack lip in Inconel side, the necking is also very important and not taken into account. The Crack lengths calculated with DDP methods give similar JR curves, than those calculated with compliance method, but without the phenomenon of decreasing crack length.

RESULTS OF FRACTURE TESTS

Analysis of CT12.5 and CT25 specimens

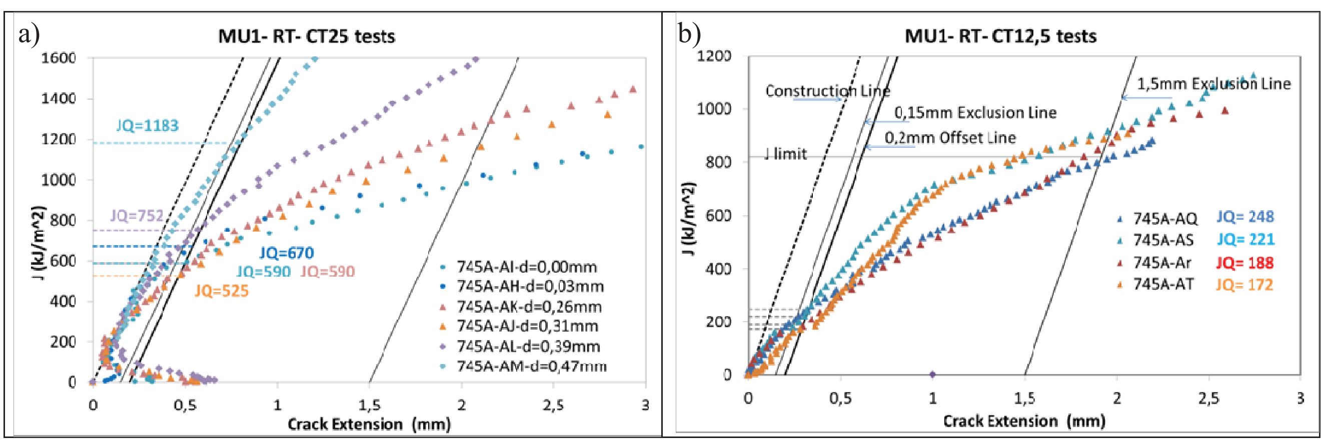


Figure 7: J-R curves, CT specimens: a) CT25 and b) CT12.5 (slope σy = (385+600)/2, M=4).

No unstable fracture has been recorded in the tests. All CT specimens results are compared in term of J-R curves (Figure 7). For the same location of the crack (at fusion line between Inconel and ferritic steel), the resulting J-R curves obtained on CT25 are very different from those obtained on CT12.5 where there is no phenomenon of decreasing crack extension in that last case. The comparison shows a great difference at the beginning of the curve. The end of all the curves is quite similar when the crack propagates across the wavy fusion line (ferritic steel and Inconel fracture surface at the same time). It can be seen that the more the crack is away from the fusion line interface; the more the ductile tearing is difficult. In conclusion, the ductile tearing resistance of the DMWinc is very high.

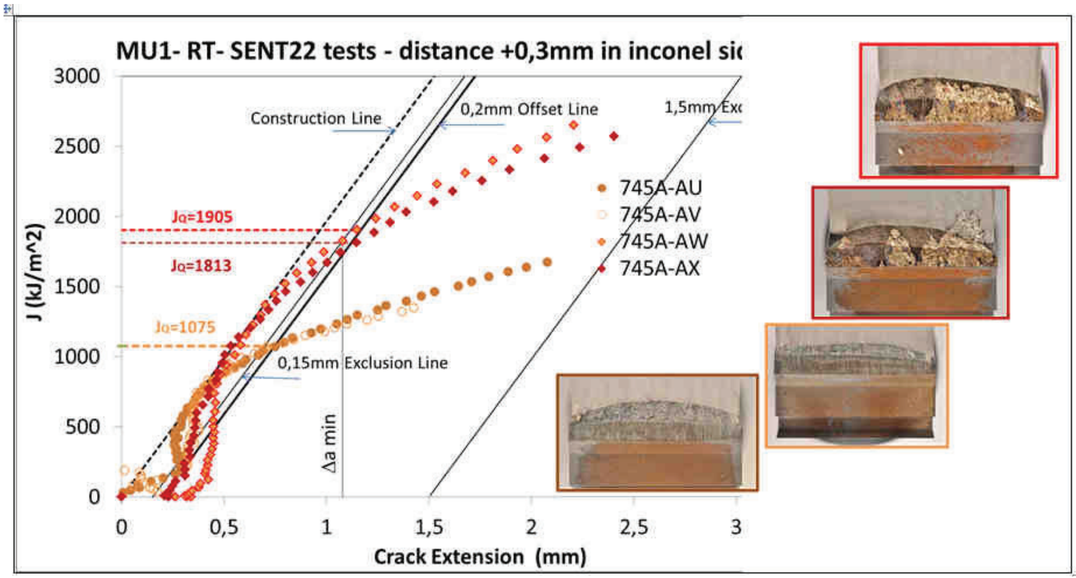


Figure 8: J-R curves, SENT specimens, cracks put at fusion line or in Inconel side.

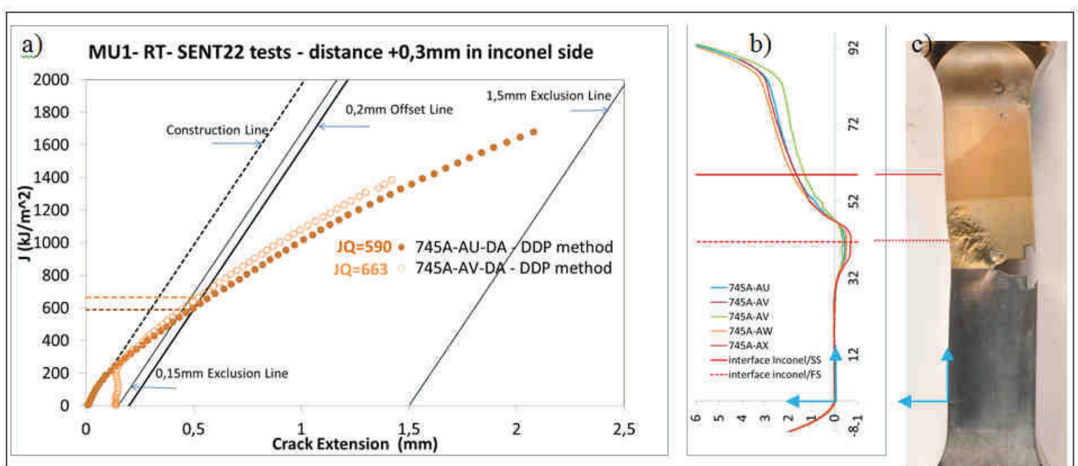


Figure 9: SENT specimens: a) J-R curves with Δa calculated by using PDD, (AU, AV),
b) Deflection measurements on back sides (AU to AW) and c) deformation view of AV.

Analysis of SENT22 specimens

The crack grew in a stable manner, J integral and J-R curve are the test results. The values of J_Q are very high values (Figure 8), J_Q is defined in the standard, J_Q correspond to $J_{0,2}$ under certain conditions, those conditions are satisfied for CT specimens only. Crack growth calculated by the help of PDD measurements, allows obtaining significantly decreasing values of J_Q much more in accordance with previous values on SENB or CT. It is possible only for the specimens AU and AV (Figure 9). Unsymmetrical multi-material specimen, high level of plastic strain located mostly in Inconel but also in

FS and the grip conditions, (fixed grip, but rotation allowed by plastic deformation), make it particularly questionable use of existing standard.

Analysis of SENB10x20 specimens

J-R curves of the six SENB 10×20 specimens are presented in (Figure 10). J_Q cannot be calculated in all the case if the blunting lines is the same whatever the location of the crack. That is why the factor M is varying to build the slope of the blunting line.

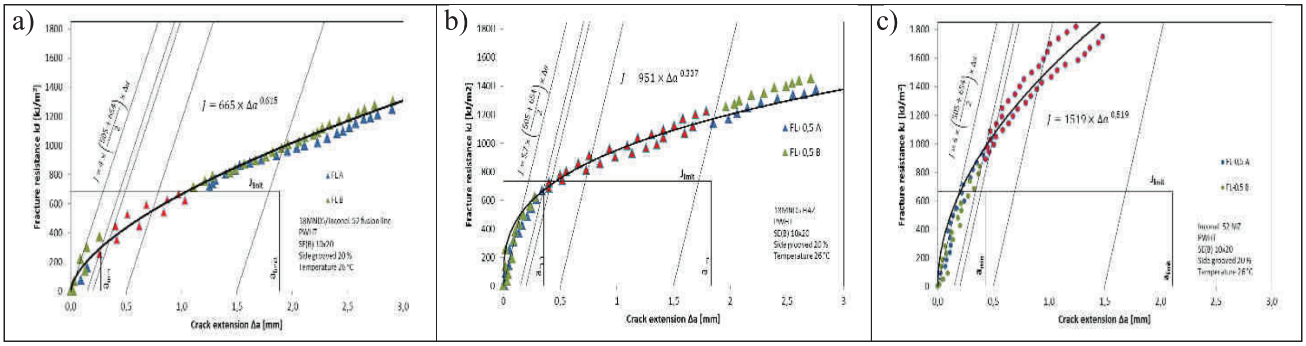


Figure 10: J-R curves for SENB 10x20 specimens: choice of M=4, 5.7 or 6 respectively for specimens with cracks put at a) FL, b) Inconel side and c) FS side.

CONCLUSION

Ductile tearing tests on CT specimens characterizing dissimilar metal welding in the vicinity of the Inconel/ferritic interface were carried out in CEA's and VTT 's mechanical testing laboratories using the ASTM-E1820 or DNV standards. Those standards are used in order to present experimental results without the need of F.E. analysis. The discussion on the limit of validity of the standard applied in the case of multi-material is not the purpose in that paper. Nevertheless, some limitation is shown: the crack extension in CT25 and SENT22 are not correctly evaluated with compliance method at the beginning of the test (negative crack extension). On the SENT22, the J_Q values are very high than on other specimen Figure 11). The JQ depends of the choice of the blunting line. For SENB analysis, the choice to change M values in function of the location of crack to build the blunting line seems to give results more in accordance with previous results CT25 tests. Despite the fact the J_Q values are not correctly evaluated on CT25 and SENT, the effect of crack location shows that crack located near fusion line, in Inconel side are very resistant. The weakest location in the DMWinc is the area of the wavy fusion line (Figure 11). The next work will consist of FE analysis of all the CT specimens in 3D calculations, and by using the J evaluation by FE, the new eta and gamma functions could be also determined and compared to those given by the standard. The plasticity and the blunting phenomenon can be study by F.E. The validity of the standards (choice of blunting line) can be also discussed and new functions can be proposed for specific multi-material specimen.

ACKNOWLEDGMENTS

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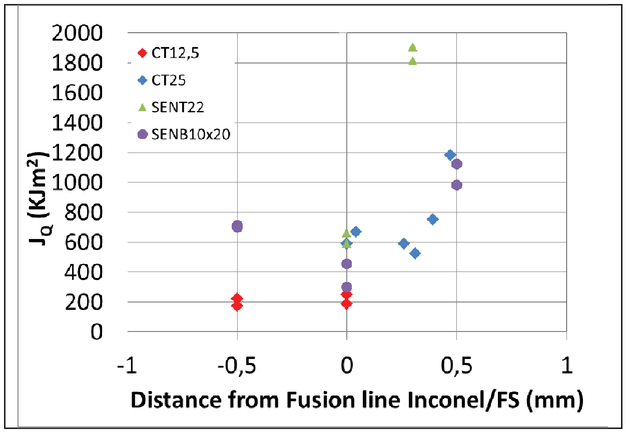

Figure 11: J_Q values function of the crack location: comparison for all fracture test specimens.

NOMENCLATURE

Inconel	Nickel alloy, alloy 52
FS	Ferritic Steel
CT	Compact Tension specimen
SENT	Single Edge Tensile specimen
SENB	Single Edge Bending specimen

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