

Fracture toughness of European reference RAFM steel EUROFER97

E. Gaganidze^{a,*}, D. Terentyev^{b,c}, M. Serrano^d, P. Lamagnère^e, M. Walter^a,
T.T.M. Nguyen^a, A. Zinovev^b, D. Bermúdez Parra^{b,f}, G. Pintsuk^g, G. Aiello^h,
M. Zmitkoⁱ, Y. Poitevinⁱ

^a Karlsruhe Institute of Technology (KIT), Institute for Applied Materials, Hermann-von-Helmholtz-Platz 1, Eggenstein-Leopoldshafen, 76344, Germany

^b Belgian Nuclear Research Centre, SCK CEN, Mol, 2400, Belgium

^c Department of Materials, Textiles and Chemical Engineering, Ghent University, Technologiepark 46, Zwijnaarde (Ghent), B-9052, Belgium

^d CIEMAT, Avd, Complutense 40, Madrid, 28040, Spain

^e CEA, DES, IRESNE, Nuclear Technology Department, Cadarache, Saint-Paul-Lez-Durance, F-13108, France

^f Institute of Mechanics, Materials and Civil Engineering (iMMC), Université Catholique de Louvain, Louvain-la-Neuve, Belgium

^g Forschungszentrum Jülich GmbH, Institute of Fusion Energy and Nuclear Waste Management – Plasma Physics, Jülich, 52425, Germany

^h EUROfusion PMU, Boltzmannstraße 2, Garching, 85749, Germany

ⁱ Fusion For Energy, Josep Pla, 2, Torres Diagonal Litoral B3, Barcelona, 08019, Spain

ARTICLE INFO

Keywords:

Reduced Activation Ferritic/Martensitic steel
Fracture toughness

ABSTRACT

RAFM steel EUROFER97 is the European reference structural material for the ITER Test Blanket Module (TBM) and the DEMONstration fusion power plant. Fracture toughness belongs to the key mechanical properties needed for the assessment of the structural integrity of the nuclear components under monotonic mechanical loading. Aiming at the support of implementation of EUROFER97 in RCC-MRx by F4E, the EUROfusion MAT-TBM group carried out fracture-mechanical characterization of the third and fourth batch of EUROFER97 in a temperature window between RT and 550°C. The resistance curve methodology implying the Unloading Compliance (UC) measurement according to ASTM E1820 standard has been proposed as the reference approach for the determination of the crack resistance curve and elastic-plastic fracture toughness J_{IC} . The application of the UC method, however, yielded so called ‘negative crack growth’ phenomena at the initial loading stage prior to onset of physical crack growth, which was corrected by appropriate offsetting the J-R curve. Furthermore, the compliance was found to be largely scattered particularly at elevated temperatures. The observed apparent negative crack growth and compliance scattering prevented the elastic plastic fracture toughness J_Q from being qualified as the test standard conform J_{IC} . Fractographic analysis revealed complex, 3D growth of ductile cracks. To back up the resistance curve J-R results, the Normalization Data Reduction Technique and Basic Procedure have been implemented. Significant quantitative differences have been observed both in the J-R behavior and J_Q values between the third and fourth batch of EUROFER97, even though both batches exhibited high toughness in the investigated temperature range. The temperature dependence of the toughness are discussed and the toughness values obtained by different methodologies and different labs are compared systematically.

1. Introduction

Reduced Activation Ferritic/Martensitic (RAFM) steel EUROFER97 is the European reference structural material for the ITER Test Blanket Module (TBM) [1] and the future DEMONstration fusion power plant (DEMO) [2]. Application of EUROFER97 in the ITER-TBM being under construction in Cadarache, France requires its qualification according to French RCC-MRx code (design and construction rules for mechanical

components of advanced reactors, research reactors and fusion reactors) [3,4]. Fracture toughness belongs to the key mechanical properties needed for the deterministic structural integrity analysis of the nuclear components under monotonic mechanical loading. Extensive studies have been performed in the past to characterize fracture toughness reference temperature (T_0) according to ASTM E1921 [5] on EUROFER97, both in the unirradiated and irradiated states, see e.g. [6–10]. Contrary to this, the available ductile fracture toughness data enabling

* Corresponding author at: Karlsruhe Institute of Technology, Institute for Applied Materials, Eggenstein-Leopoldshafen, Germany.

E-mail address: ermile.gaganidze@kit.edu (E. Gaganidze).

<https://doi.org/10.1016/j.fusengdes.2026.116072>

Received 12 June 2026; Received in revised form 31 August 2026; Accepted 20 September 2026

Available online 5 October 2026

0920-3796/© 2026 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Open access funding enabled and organized by Projekt DEAL.

the evaluation of crack extension resistance behavior is rather scarce and mainly limited to the 1st and 2nd batch of EUROFER97 see e.g. [11–14]. Moreover, due to violation of the requirements of relevant ASTM E1820 [15] and ISO 12135 [16] testing standards on the specimen dimensions, guarantying prevailing plane strain condition along the crack front (across the specimen thickness), the available elastic-plastic fracture toughness and *J*-*R* curve data cannot be always classified as valid and thus should not be recommended for design application. Crack extension resistance *J*-*R* curves are in a probationary rule of Afcen RCC-MRx code [4], however results on more batches (at least two) will be required for the analysis of the dispersion of results. Widely accepted practice for construction of the crack growth resistance curve is application of the resistance curve test method in combination with the measurement of Unloading Compliance (UC) adopted by various testing standards including ASTM E1820 and ISO 12135. Utilization of a single specimen only for the construction of a whole *J*-*R* curve makes the application of this method very attractive. The uncertainties in the determination of the crack length from the measured unloading compliance as well as apparent negative crack growth observed for high toughness materials [17,18], however, makes this approach less precise compared to the Basic Procedure (BP) described in section 8.4 of the ASTM E1820-25 testing standard, the latter requiring however testing of more (at least five) specimens in the eligible $J - \Delta a$ space. An apparent negative crack growth is observed for both, high toughness ferritic and austenitic steels [18]. Such behavior is ascribed to compressive residual stress caused by the plastic zone around crack tip during unloading process in [17], whereas strain hardening of the material during the blunting process is considered to be the main reason in [18]. Misalignment of the loading train, friction and physical blunting behavior are alternatively considered as possible reasons for apparent negative crack growth [19]. For a recent literature review on the apparent negative crack growth the reader is referred to [20] and references therein. In addition, during the examination of type 316L stainless steel, Chen et al. pointed out that the UC method becomes impractical in elevated temperature testing due to stress relaxation of the material and enhanced friction interference between the specimen, pin and clevis which results in unreliable crack size measurements [21]. Application of the Normalization Data Reduction Technique (NDRT) according to ASTM E1820-Annex A15 relieves technical difficulties related to the testing of a single specimen, as monitoring of the crack growth with progressing load line displacement (LLD) is no more required, see e.g. [15,16,22]. The advancement of the crack is instead calculated by taking into account recorded force vs. LLD curve as well as physically measured initial and final crack lengths by assuming unique relationship between the force, the displacement and the crack length [23].

Current paper deals with the determination of *J*-*R* behavior and plane strain fracture toughness of two batches of EUROFER97. Joint efforts of EUROfusion MAT-TBM group have been utilized to characterize the material in a wide temperature window between RT and 550°C. The difficulties related to the determination of fracture toughness of high toughness materials will be addressed. The toughness values obtained by different methodologies and different labs will be compared systematically. The data from the involved labs will be consolidated and discussed in terms of the temperature and batch dependence. The generated data is intended to be used by F4E for implementation of EUROFER97 in Afcen RCC-MRx code.

2. Experimental

2.1. Material

Material studied in the current work is batch 3 (EUROFER97-3) and batch 4 (EUROFER97-4) of RAFM steel EUROFER97 produced by Saarschmiede GmbH Freiformschmiede [24]. Manufacturing steps involved melting in a Vacuum Induction Melting (VIM) furnace, remelting using a Vacuum Arc Remelting (VAR) furnace, forging, rolling

and final thermal treatment. The nominal chemical compositions of EUROFER97 are well met by batch 3 and batch 4 as shown by the manufacturers' analysis given in Tables 1 and 2, respectively.

A 50 mm thick plate (EUROFER97-3, heat 994570) and a 46.5 mm thick plate (EUROFER97-4, heat 988590) have been chosen for the fracture toughness study. The identification numbers assigned to the plates by the manufacturer are ID48 and ID70, respectively. Final heat treatment applied by the manufacturer included normalization at 980°C for 50 min followed by air cooling and tempering at 760°C for 145 min for ID48 and normalization at 980°C for 90 min followed by cooling with forced air and tempering at 740°C for 55 min for ID70. Having two different heat treatments helps us to demonstrate that the domain of valid manufacturing is covered by the fracture toughness tests. Tensile properties used for the evaluation of the crack resistance curves are summarized in Table 3.

2.2. Specimen manufacturing, testing and evaluation

Labs from three European countries participated in the fracture toughness characterization campaign: CIEMAT (Spain), SCK-CEN (Belgium) and KIT (Germany). It was agreed to use Compact Tension (C(T)) specimens of a common specimen thickness of $B = 20$ mm. All other dimensions were scaled according to the ASTM E1820 standard, i. e. specimen width $W = 2 \cdot B = 40$ mm, etc. Specimens have been extracted in T-L orientation, with T denoting the long transverse direction and L denoting longitudinal (rolling) direction of the plate. Two specimens have been extracted through the plate short thickness direction. All specimens have been subjected to fatigue loading at RT at a load ratio of $R = P_{\min}/P_{\max} = 0.1$. Maximum load during pre-cracking was always below the limit specified in ASTM E1820, i.e. below

$$P_m = \frac{0.4Bb_o^2\sigma_Y}{2W + a_o} \quad (1)$$

Here a_o is the initial crack length, b_o - the original remaining ligation of the C(T) specimens and σ_Y - the mean of yield strength and the ultimate tensile strength. The applied maximum stress intensity factor has been reduced in the final phase of fatigue pre-cracking as recommended by ASTM E1820. Pre-cracking frequency varied in a range of 25–30 Hz. A ratio of the initial crack length a_o to specimen width (W) was in a range of 0.5–0.6. All specimens were side-grooved after fatigue pre-cracking to a depth of 10% of the specimen thickness on both sides (resulting net thickness of $B_n = 16$ mm) utilizing root radii of 0.25–0.5 mm and groove angles of 45–60°. All specimens have satisfied the straightness criteria for the specimen crack front as prescribed by ASTM E1820.

High temperature (HT) Crack Opening Displacement (COD) gages from Epsilon technology corporation [26] of different configurations adapted to the testing setups of individual labs have been used for the measurement of the displacement. Calibration of the extensometers has been done at test relevant temperatures by means of Linear Variable Differential Transformer (LVDT) gages. CIEMAT experienced difficulties with the COD extensometer during the initial tests, where the test displacement rate was controlled using the extensometer signal. This caused significant scatter in the load-line displacement signal during the unloading/reloading cycles, compromising the compliance-based crack size measurement according to ASTM E1820. When the test rate was controlled using the machine LVDT instead, the signal stabilized. KIT has utilized Front Face Displacement (FFD) measurement by means of integral knives machined at the front face of the specimen. SCK-CEN and CIEMAT directly measured Load Line Displacement (LLD). The FFD measured by HT COD gage at KIT has been converted to the LLD taking into account the position of FFD measurement by applying a formula proposed by Landes [27]

$$\frac{LLD}{FFD} = \frac{a + rb}{a + rb + c} \quad (2)$$

Table 1

Chemical composition of EUROFER97-3, Heat 994570 in wt%, Fe balance.

	C%	S%	P%	Si%	Mn%	Ni%	Cr%	Mo%	W%	As+Sn+Sb+Zr%
min	0.09	-	-	-	0.20	-	8.50	-	1	0
max	0.12	0.005	0.005	0.050	0.60	0.01	9.50	0.005	1.2	0.05
Top near surface	0.098	0.0032	0.0013	0.025	0.53	0.01	9.11	0.002	1.11	< 0.007
Top centre	0.101	0.0035	0.0014	0.025	0.53	0.01	9.1	0.002	1.11	< 0.007
Bottom centre	0.103	0.0032	0.0012	0.025	0.53	0.01	9.1	0.003	1.11	< 0.007
	Ta%	V%	Nb%	Cu%	B%	Al%	Co%	N ₂ %	Ti%	
min	0.10	0.15	-	-	-	-	-	0.015	-	
max	0.14	0.25	0.005	0.01	0.002	0.01	0.01	0.045	0.02	
Top near surface	0.11	0.20	0.004	0.003	0.0011	0.002	0.003	0.029	0.001	
Top centre	0.11	0.20	0.004	0.003	0.0010	0.002	0.003	0.035	0.001	
Bottom centre	0.11	0.20	0.004	0.003	0.0011	0.003	0.003	0.035	0.001	

Table 2

Chemical composition of EUROFER97-4, Heat 988590 in wt%, Fe balance.

	C%	S%	P%	Si%	Mn%	Ni%	Cr%	Mo%	W%	As+Sn+Sb+Zr%
min	0.09	-	-	-	0.20	-	8.50	-	1	0
max	0.12	0.005	0.005	0.050	0.60	0.01	9.50	0.005	1.2	
Top	0.09	0.005	0.002	0.021	0.45	0.008	8.6	0.002	1.1	0.0049
Bottom	0.09	0.005	0.002	0.021	0.46	0.008	8.6	0.002	1.1	0.0049
	Ta%	V%	Nb%	Cu%	B%	Al%	N ₂ %	Ti%	Co%	O ₂
min	0.10	0.15	-	-	-	-	0.015	-	0.01	-
max	0.14	0.25	0.005	0.01	0.002	0.01	0.045	0.02	0.04	0.01
Top	0.13	0.20	0.005	0.004	0.001	0.002	0.029	0.001	0.004	0.001
Bottom	0.13	0.20	0.005	0.004	0.001	0.002	0.036	0.001	0.007	0.001

Table 3

Tensile properties used for evaluation of fracture toughness of batch 3 [3] and batch 4 [25]. Values given in the parenthesis were used by CIEMAT for batch 3.

Batch	Temperature (°C)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Young's modulus (GPa)
Batch 3	RT	541 (532)	668 (654)	217
Batch 3	300	471	548	202
Batch 3	350	457	525	199
Batch 3	450	412 (403)	465 (453)	193
Batch 3	550	332	371	180
Batch 4	RT	604.0	694.4	217
Batch 4	300	521.1	567.2	202
Batch 4	350	517.2	556.2	199
Batch 4	450	474.1	502.3	193
Batch 4	550	368.7	377.0	180

Here a denotes the crack length of a C(T) specimen, b – the ligament length, c – the distance from the load line to the point of the FFD measurement and r is the distance from the crack tip to the point of rotation divided by b . ASTM E1820 makes use of $r = 0.5$ for calculation of a point of specimen rotation.

Servo-hydraulic universal testing machines equipped with high temperature furnaces available at the participant's labs have been used for fracture toughness testing. The calibrated thermocouples have been attached to the C(T) specimens directly. Loading of the specimen has been utilized in displacement controlled mode by all labs at a

displacement rate of 0.2–0.6 mm/min. Partial unloading of the specimens for the UC measurement has been performed either in a displacement controlled mode by KIT (unloading/reloading rate 0.6 mm/min) and by SCK-CEN (unloading/reloading rate 0.2 mm/min) or in a load controlled mode by CIEMAT (unloading/reloading rate of 8 kN/min). KIT did not implement hold time prior unloading events, instead initial non-linear parts of unloading sections have been discarded in order to analyze the compliance of remaining quasi-linear curves. SCK-CEN implemented hold times of 15 s and 200 s for low and high temperature tests, respectively. As for CIEMAT, a constant hold time of 15 s was used in the entire temperature range. All tests have been performed under air. The apparatus used by SCK-CEN is accredited through the Belgian national safety authority. The test matrix covered the following temperatures: RT, 300, 350, 450, 550°C. The targeted crack extension values were first $\Delta a = 0.5, 1, 1.5$ mm then extended up to 3 mm. These targets were chosen in order to improve confidence in the single specimen J_{IC} values and J-R curves determined either by UC or NDRT by application of the Basic Procedure.

After testing, the specimens were cooled down and subjected to RT cycling load to further reduce the remaining ligament (b) before their final separation into two halves by applying tearing load in tension at KIT. The post fracture toughness test fatigue cracking is done to the extent when the specimen necking is recovered. Under such circumstances we do not expect substantial distortion of ductile crack front and necking. Alternatively, at SCK-CEN and CIEMAT, the specimens have cooled down to liquid nitrogen temperature and separated by brittle fracture. In some cases, SCK-CEN also performed fatigue cracking after the end of J-R test to create a new fatigue line. Initial and final crack lengths have been measured under optical microscope. Determination of a final physical crack size (a_p) could not be performed according to ASTM E1820. Necking of the C(T) specimens prevented the physical crack size measurements at both of the outer positions (red lines in Fig. 1) of 9 equally spaced points extending to 0.005 W from the roots of the side grooves. An alternative procedure is indicated in Fig. 1 where only 7 positions (green lines) are used for the determination of a physical

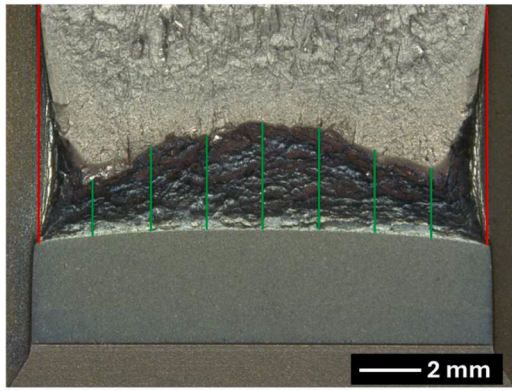


Fig. 1. Fracture surface of a C(T) specimen tested at 350°C indicating positions for crack advancement measurement according to ASTM E1820. Position marked by green lines are adopted for crack growth measurement in current work.

crack length a_p by means of simple arithmetic averaging of the 7 records.

2.3. Test evaluation procedure

When using an elastic compliance technique, the crack size for each unloading sequence ($a_{(i)}$) is calculated from the elastic compliance $C_{c(i)}$ after correction for rotation according to the ASTM E1820.

For construction of the resistance curve the calculation of the $J_{(i)}$ integral for each set of the crack length $a_{(i)}$, the displacement $v_{(i)}$ and the load $P_{(i)}$ is performed as follows

$$J_{(i)} = \frac{(K_{(i)})^2(1 - \nu^2)}{E} + J_{pl(i)} \quad (3)$$

where stress intensity factor $K_{(i)}$ and plastic part of the J integral ($J_{pl(i)}$) for respective crack length are calculated according to the ASTM E1820 procedure for the C(T) specimens. Furthermore, optically measured crack growth Δa have been used for construction of J -R curves according to the BP of ASTM E1820 standard.

In addition, construction of J -R curves on the base of optically measured initial and final crack lengths and recorded force vs. LLD curves have been performed in compliance with the NDRT described in the Annex 15 of ASTM E1820. Constructed J -R is considered valid if a normalization function fits the normalized force displacement curve with a maximum deviation below 1% of the final normalized force point.

The interim fracture toughness value J_Q is determined as the ordinate of the intersection of the $J = C_1 \Delta a^{C_2}$ fit to constructed $(\Delta a_{(i)}, J_{(i)})$ points and 0.2 mm offset of the $J = 2\sigma_Y \Delta a$ construction line, with σ_Y being a mean of the yield strength and the ultimate tensile strength. The data-points eligible for the fit are confined by 0.15 mm and 1.5 mm offset construction lines and $J_{limit} = \frac{b_0 \sigma_Y}{7.5}$ as described in ASTM E1820.

Furthermore, the maximum J -integral capacity, $J_{max} = \min\left(\frac{b_0 \sigma_Y}{10}, \frac{B \sigma_Y}{10}\right)$ and maximum crack extension capacity, $\Delta a_{max} = 0.25b_0$, have to be taken into account.

Following the ASTM E1820 when using the UC technique all $(\Delta a_{(i)}, J_{(i)})$ points that were determined before reaching the maximum force are used to calculate revised initial crack length a_{oq} . To achieve this the above described points will be fitted to

$$a = a_{oq} + \frac{J}{2\sigma_Y} + BJ^2 + CJ^3 \quad (4)$$

where a_{oq} , B , C are found using a least square procedure. If the optically measured crack size, a_o , differs from a_{oq} by more than the larger of

0.01W or 0.5 mm, the data set is not adequate according to the ASTM E1820 test method.

3. Results

The results of a preliminary evaluation of some of the tests have been partly reported in [28]. For the sake of completeness and comparison, we will present all results obtained within the current characterization campaign. An example of a recorded load vs. LLD curve and subsequent evaluation steps towards construction of crack resistance J -R curve is shown in Fig. 2. The material tested is the ID70 plate and the testing temperature equals to 300°C. Partial unloadings were implemented during testing aiming at the determination of the UC, see Fig. 2 (a). The unloading compliance determined via analysis of the unloading sections of the curve is shown in Fig. 2(b). A striking feature is a minimum seen in unloading compliance vs displacement dependence. The appearance of this minimum leads to an apparent negative crack growth observed in the constructed crack resistance J -R curve, see Fig. 2(c). The ASTM E1820 does not provide a procedure for the treatment of the negative crack growth. Instead, the test is requested to be stopped if crack length changes by more than $0.005a_0$. We note that an apparent negative crack growth prevents application of Eq. 4 for determination of the revised initial crack length a_{oq} and thus does not allow examination of one of the criteria of the ASTM E1820 testing standard for qualification of the results. To allow analysis of the J -R behavior and the determination of the J_Q , the J -R curve has been offset in a way to match its quasi-linear part, originating in the blunting of the crack tip, to the $J = 2\sigma_Y \Delta a$ construction line. This approach is slightly different from the so called offset technique [17,20]. The difference is that in [17] the J -R curve is shifted along the crack growth axis by an amount of distance from the most negative Δa point, whereas in the current work an appropriate Δa shift is identified by taking into account a scattering of the data in the blunting region. In [18] another alternative approach has been proposed for correction of an apparent negative crack growth. This includes i) identification of the minimum in the compliance vs displacement dependence (in original paper: maximum in stiffness vs displacement dependence); ii) discarding the datapoints left to the minimum, iii) smooth conversion of the measured compliance into corrected compliance taking into account expected compliance values corresponding to physically measured initial and final crack lengths (shown by green symbols in Fig. 2(b)) and iv) placing the crack growth initiation point (corresponding to the minimum compliance) onto the blunting line. The J -R curve constructed following the compliance correction procedure proposed in [18] is also included in Fig. 2(c). Finally, the solid magenta line in Fig. 2(c) presents the J -R curve constructed by application of NDRT of ASTM E1820. The intersection of the constructed J -R curves with 0.2 mm offset construction line yielded J_Q values of 325.4 kJ/m², 278.7 kJ/m² and 373.9 kJ/m² for the resistance curve (simple offset of Δa used in the current work), compliance correction procedure [18] and NDRT, respectively. Difference in J_Q values between the simple Δa offset and compliance correction approaches is of the order of 14%. The NDRT yields the highest J_Q value (~15% higher than simple Δa offset) for the current specimen. An alternative treatment of the apparent negative crack growth based on the fitting of $a(J)$ dependence to eliminate the arbitrary shift of the crack length, was reported to yield higher J_{lc} values for austenitic stainless steel when compared to the treatment implying zero shifting of the most negative Δa values [19]. We note that the scattering of the compliance may prevent identification of the location of the minimum in the compliance vs displacement dependence. Due to above described observations, and due to lack of a widespread consensus on the correction of an apparent negative crack growth, a simple Δa offset approach, implying offset of J -R curve by matching its quasi-linear part to the blunting line, was adopted throughout this work. Regarding the implementation of EUROFER97 into Afcen RCC-MRx, for the cases where only the results from the UC test method are available, to validate

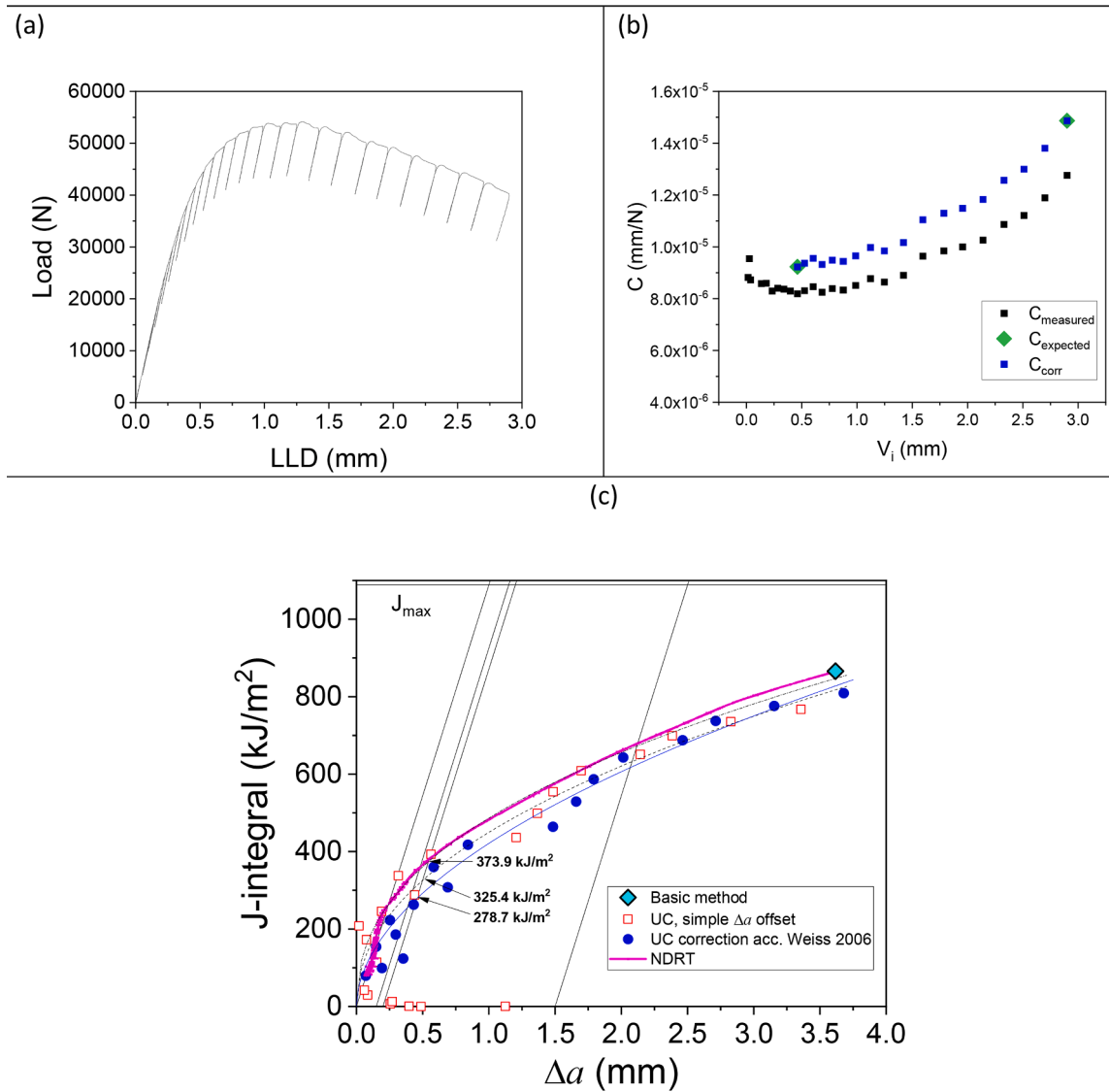


Fig. 2. Fracture-mechanical test and evaluation of ID70 at 300°C. (a) Load vs LLD curve; (b) Measured, expected and corrected compliances; (c) J-R curves constructed by utilizing the UC in resistance curve procedure after simple Δa offset (red squares), the UC after compliance correction according to the procedure proposed in [18] (dark blue circles) and J-R curve constructed according to the NDRT (solid magenta line). A $J = 2\sigma_Y \Delta a$ construction line and its offsets according to ASTM E1820 together with enabled $J_{\max}$ value are also included. The dotted black and solid blue lines represent $J=C_1(\Delta a)^{C_2}$ fit to the eligible datapoints obtained by the resistance curve procedure and the compliance correction method, respectively.

the existing results and to minimize uncertainties introduced by the negative crack growth, we recommend repetition of fracture toughness tests by utilizing alternative methods (such as the BP).

Fractographic examination of the broken specimens under Scanning Electron Microscope (SEM) revealed extended stretched zone, followed by complex, three-dimensional crack growth, see Fig. 3 (a) and (c). The formation of ductile dimples as a result of nucleation, growth and coalescence of the micro-voids appears to be the dominant mechanism for the ductile crack growth, see Fig. 3 (b) and (d). Though not quantitatively assessed, the size distribution of equiaxed dimples seems to be more heterogeneous after testing at 550°C.

The $J = C_1 \Delta a^{C_2}$ power law fits determined by the labs by means of the resistance curve procedure and NDRT are shown in Fig. 4. In addition, limited data from the BP are also included when number of tested specimens was more than one per testing condition. In all cases the results obtained by the BP cannot be considered valid according to the requirements of the standards due to an insufficient number of available tests in the eligible $J - \Delta a$ space. Due to limited number of available specimens, systematic lab-to-lab reproducibility was not studied in the

current work. ID70 specimens were tested at 450°C by KIT and CIEMAT, see Fig. 4 (i). Application of UC and NDRT techniques by KIT and NDRT technique by CIEMAT provide a moderate scatter of the data (mean: 212 kJ/m², standard deviation ± 37 kJ/m²). The repeatability of the J-R curves and J_Q results within each lab is satisfactory independently whether the UC or NDRT is used. The scattering is particularly low when the tests are performed at or below 350°C. Exceptions were observed at RT by SCK-CEN where the application of the UC technique at RT yielded nearly linear J-R curves due to apparent overestimation of the crack growth measurement, see Fig. 4 (a) and (f). Crack segmentation and its propagation in multiple planes caused by high RT fracture toughness of the material in addition to possible sliding of COD gage knives may obscure the crack length determination by the UC. Corresponding J_Q values are strongly underestimated when compared with the results obtained by the NDRT. The application of the BP leads to overestimation of J-R curve compared with the UC or NDRT results in some cases where available datapoints are far from the 0.2 mm offset line, see e.g. Fig. 4 (d) and (e). In other cases, the results from the BP may be consistent with the resistance curves obtained by the UC or NDRT approaches. ASTM

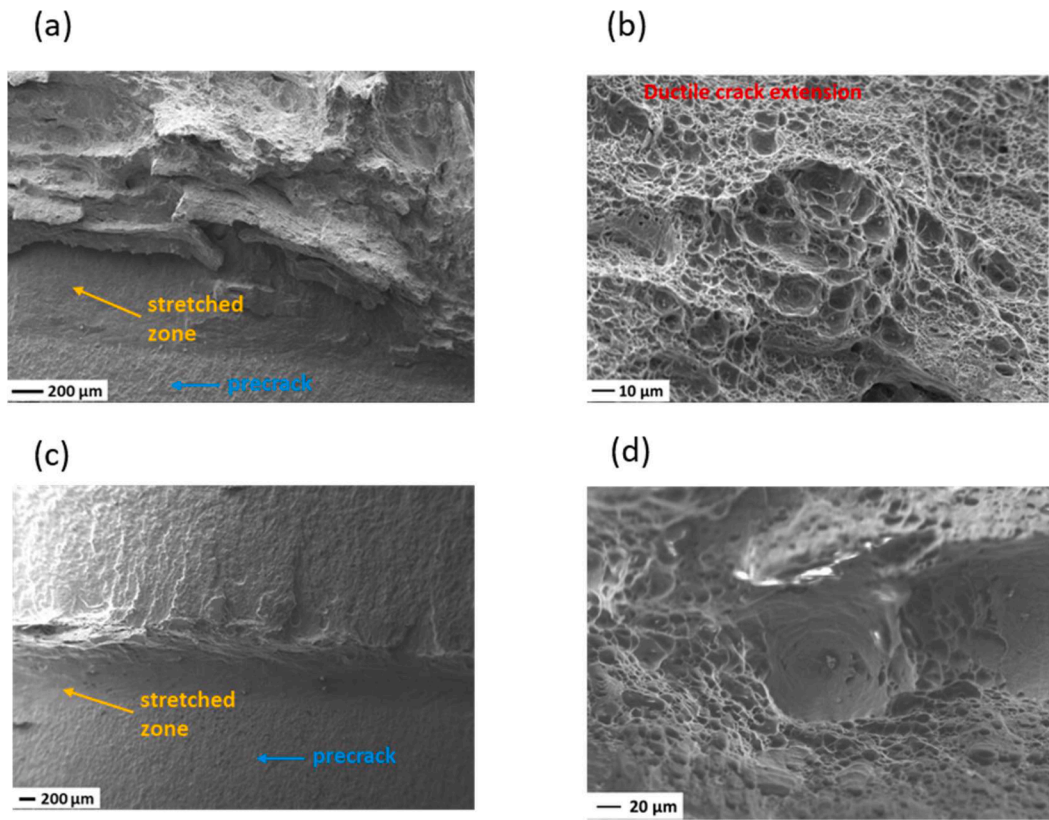


Fig. 3. (a) SEM image of ID48 specimen after testing at 350°C revealing stretched zone; (b) SEM image of ID48 specimen after testing at 350°C revealing extensive dimple formation during crack growth; (c) SEM image of ID48 specimen after testing at 550°C revealing stretched zone; (d) SEM image of ID48 specimen after testing at 550°C revealing dimple formation.

E1820 requires availability of at least 5 datapoints in a qualified area with one of the datapoints between 0.15 and 0.5 mm offset lines, see test and evaluation procedure in section 2. The availability of too few datapoints within the current work prevents however reliable determination of the J -R curve and fracture toughness via the BP – a small error in a single datapoint may act as a source for large error in the constructed resistance curve.

The temperature evolution of J -R curves is summarized in Fig. 5 (a) for ID48 and Fig. 5 (b) for ID70 plates, respectively and the corresponding C_1 and C_2 coefficients are listed in Table 4. A remarkable reduction of the resistance against crack growth is observed when increasing the temperature from RT to 300–350°C for both materials. With further increase of the temperature, however, no clear tendency on J -R curves can be recognized, even though the curves for ID48 are slightly inferior compared with the ones determined at 300–350°C. As for ID70, the resistance curve appears to be superior at 550°C when compared to the behavior observed at 350–450°C. The ID48 shows higher resistance against crack growth compared to ID70 plate in the entire investigated temperature range.

To examine the temperature evolution of fracture toughness, the results from UC, NDRT and BP have been collated and presented in Fig. 6 for ID48 and Fig. 7 for ID70, respectively. For the analysis purpose, the negative crack growth alone was not considered to be a data disqualifying criterium. In the case of ID48 plate the BP appeared to overestimate the results compared to UC or NDRT at elevated temperatures. In the case of ID70, however, good agreement is seen between the results obtained by the BP on the one hand and by UC or NDRT methods, on the other hand. Nevertheless, all J_Q results obtained according to the BP have been excluded from the analysis due to insufficient number of underlying tests in eligible $J - \Delta a$ space. Moreover, some of the results obtained according to the NDRT, represented with crossed symbols in Fig. 6, were also excluded from the analysis because

they were classified as invalid due to poor quality of the fit to the normalized force displacement curve, see Chapter 2. Remaining data represented by open symbols were classified as qualified and used for determination of the average toughness values included in Figs. 6 and 7 together with standard deviation values represented by error bars. The dashed lines shown in Figs. 6 and 7 are guides for the eye. The fracture toughness of ID48 and ID70 plates decreases remarkably by rising the temperature from RT to 300°C. Above 300°C the temperature evolution of the toughness of ID48 is weak and slightly non-monotonic exhibiting a small peak at 350°C followed by a small minimum at 450°C, see Fig. 6. As for ID70, the toughness exhibits a clearly resolved broad minimum between 350 and 450°C in Fig. 7. The two Figs. also include temperature dependence of the total elongation for the respective batches.

4. Discussion

The application of the UC technique in combination with the resistance curve procedure was found to be challenging due to i) apparent negative crack growth and ii) large scatter of the measured compliance. In the SCK test, the apparent negative crack growth seemed to be more pronounced at room temperature than at 300°C. This may suggest that mechanisms such as crack-tip strain hardening and compressive residual stresses are more dominant at lower temperature, while stress relaxation at elevated temperature may partially mitigate the effect. Irrespective of the absence of widespread consensus regarding the origin of the apparent negative crack growth, this phenomenon is known to be characteristic for high toughness steels [17–20]. Application of crack growth offsetting procedure aiming at matching of quasi-linear part of J -R curve to the blunting line is believed to be reasonable approach until a dedicated compliance correction procedure becomes available in the relevant testing standards. The scattering of the compliance was particularly high for the tests at elevated ($\geq 450^\circ\text{C}$) temperatures.

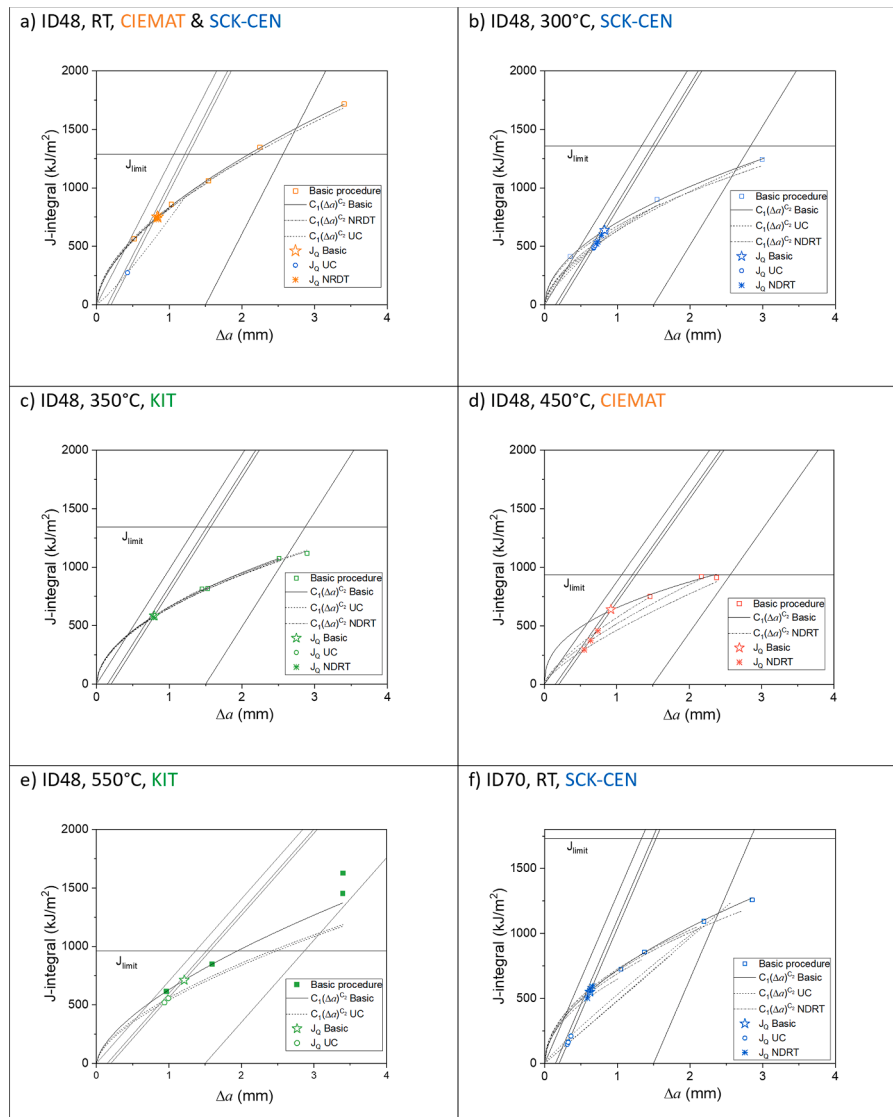


Fig. 4. $J=C_1(\Delta a)^{C_2}$ curves along with J_Q values determined by applying BP, resistance curve and NDRT. Limited number of J values from the BP are also included.

Complex, 3D crack growth and excessive blunting occurring at elevated temperatures together with potential creep effects and stress relaxation are believed to distort the compliance measurement along with factors like friction, alignment of the load train etc. reported in the literature [19,20]. At elevated temperatures the use of bulky HT extensometers may be an additional source for the compliance scattering as compared with experiments carried out in a temperature window between liquid nitrogen (-196°C) to 300°C where lightweight extensometers are used. Reversals of the loading direction required for the UC method may become a source of sliding of the extensometer knives thus introducing a scatter and/or offset into the signal resulting deterioration of the determined crack length. A wavy character of the curves observed above 0.9 mm of LLD, see Fig. 2(a), may be an indication of the Dynamic Strain Aging (DSA) effects even though serrated type flow in uniaxial tensile tests is frequently not observed for RAFM steels [29,30]. Xu and Shen [31] did report DSA effect in China Low Activation Martensitic Steel (CLAM) on the base of the observed serrated flow between 300 and 350°C and over 500°C along with plateau in the tensile and yield strengths and minimum in the ductility at intermediate temperatures. The DSA evidence during low cycle fatigue deformation in ferritic

martensitic steels was in addition reported in [32]. The investigation of strain rate effects on the tensile and fracture toughness properties could provide deeper insight in the DSA phenomena in RAFM steels. Though a factor three difference in the loading rates among different labs is not expected to affect the fracture toughness significantly, loading rates are proposed to be kept same between participating labs in order to avoid any uncertainty in the interpretation of the results.

The normalization procedure has been found to yield reproducible results particularly at temperatures less than or equal to 350°C . Partial unloadings, implied for the UC method, require post processing of the recorded force displacement curves to eliminate unloading/reloading sections for application of the NDRT. In the case of a post processed curve, however, fitting quality to normalized forced displacement curve may become poor, particularly at elevated temperatures, and deviation between fit and normalized force displacement curve may exceed maximum allowed value of 1 % of a final normalized force thus making the determined crack resistance curve invalid according to ASTM E1820. Getting rid of partial unloadings was demonstrated by CIEMAT to lead to acceptable quality crack resistance curves when applying the NDRT even at elevated temperatures, see the results in Fig. 4 (j).

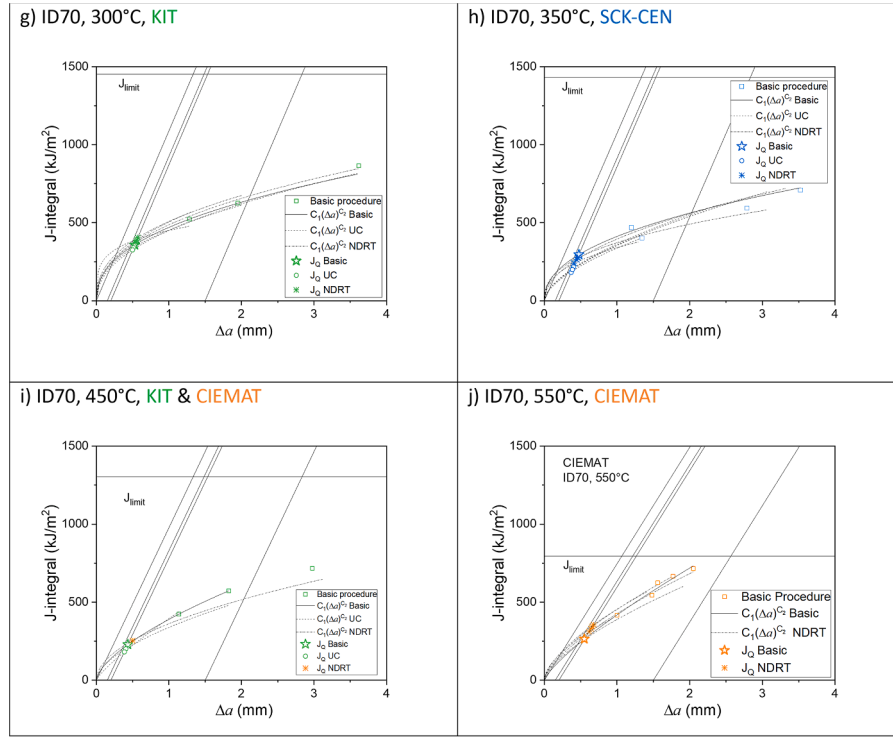


Fig. 4. (continued).

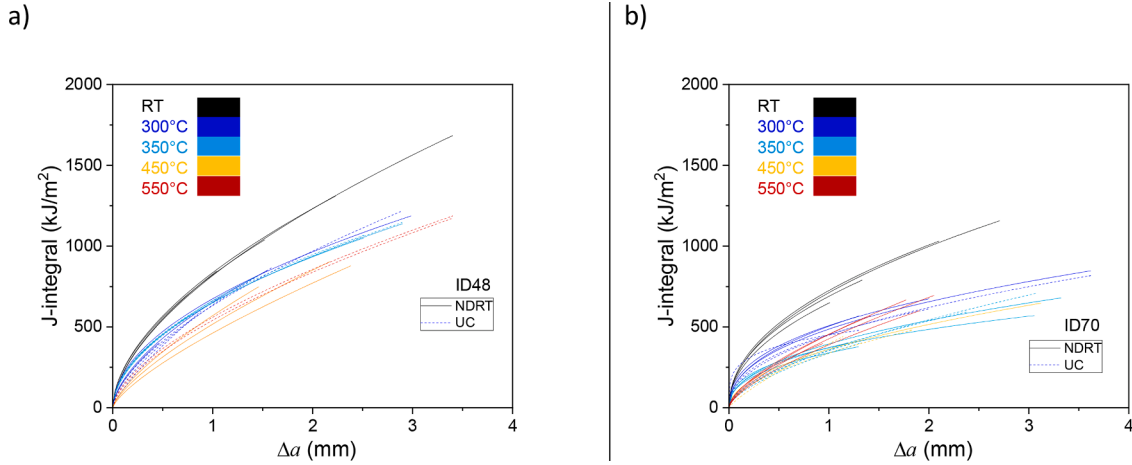


Fig. 5. J-R curves at different temperatures for ID48 and ID70 plates. For test temperature and applied evaluation technique see Fig. legend.

Comparison of the J-R curve obtained by the UC, with the curves obtained by the BP and the NDRT was systematically implied in this work depending on their availability to improve the confidence in J_Q values and J-R curves extracted from the UC. For the current analysis the qualified J_Q values obtained by the UC method were either very close to or slightly lower than the qualified values obtained by other methods. The minimum values to be calculated in Afcen RCC-MRX code will account for the scatter of the fracture toughness and thus enable conservative evaluation of the component integrity. In some cases, qualified results are available for one evaluation procedure only, see e.g. Fig. 4(e) where NDRT results are not presented due to violation of the requirement on the fitting quality or due to malfunction of the extensometer. Another example is Fig. 4(j) where no UC results are presented due to lack of partial unloadings aiming at the improvement of NDRT curve

quality. Though application of different J_Q evaluation methods is useful for the evaluation of the dispersion of the results this is not strictly requested by Afcen RCC-MRX code.

The qualified toughness data on ID48 plate, used for the determination of the average values in Fig. 6 show low scatter reflected in moderate values of standard deviation (SD). This indicates a good repeatability of the results within each lab. No systematic lab to lab reproducibility study has been done for the case of ID48 plate within this work. Whether a small maximum at 350°C with a relative height of ~10% could be attributed to a lab-to-lab bias is not clear taking into account general susceptibility of the toughness to a scatter. Furthermore, to which extent a minimum observed at 450°C is related to a broad minimum in the total elongation observed around 350°C for EUROFER97 steel, see Fig. 6, is not clear either. Remarkably, the

Table 4Tabulated values of C_1 and C_2 coefficients of $J = C_1 \Delta a^{C_2}$ curves given in Fig. 5 along with J_Q values.

ID48						ID70					
Lab	T (°C)	Method	C_1	C_2	J_Q (kJ/m ²)	Lab	T (°C)	Method	C_1	C_2	J_Q (kJ/m ²)
CIEMAT	20	NDRT	826	0.59	742	KIT	300	NDRT	508	0.41	404
CIEMAT	20	NDRT	822	0.56	745	KIT	300	UC	453	0.43	339
CIEMAT	20	NDRT	836	0.56	768	KIT	300	NDRT	486	0.43	374
CIEMAT	20	NDRT	818	0.59	730	KIT	300	UC	450	0.47	325
CIEMAT	450	NDRT	462	0.74	295	KIT	300	NDRT	505	0.45	388
CIEMAT	450	NDRT	570	0.72	458	KIT	300	UC	450	0.24	393
CIEMAT	450	NDRT	517	0.72	374	KIT	450	UC	338	0.58	201
SCK CEN	300	UC	656	0.77	484	KIT	450	UC	395	0.82	182
SCK CEN	300	NDRT	644	0.62	523	CIEMAT	450	NDRT	362	0.51	254
SCK CEN	300	NDRT	653	0.60	541	CIEMAT	550	NDRT	390	0.67	261
SCK CEN	300	UC	635	0.67	492	CIEMAT	550	NDRT	412	0.58	311
SCK CEN	300	NDRT	674	0.52	594	CIEMAT	550	NDRT	455	0.64	355
SCK CEN	300	UC	632	0.62	505	CIEMAT	550	NDRT	427	0.68	330
KIT	350	NDRT	663	0.55	583	CIEMAT	550	NDRT	454	0.67	344
KIT	350	UC	647	0.54	563	SCK CEN	25	NDRT	648	0.48	502
KIT	350	NDRT	651	0.53	573	SCK CEN	22	NDRT	690	0.47	552
KIT	350	UC	651	0.53	572	SCK CEN	21	NDRT	725	0.47	595
KIT	350	NDRT	652	0.52	575	SCK CEN	25	NDRT	712	0.49	574
KIT	350	UC	660	0.52	586	SCK CEN	350	NDRT	372	0.43	264
KIT	550	UC	560	0.61	557	SCK CEN	350	UC	354	0.57	207
KIT	550	UC	541	0.63	520	SCK CEN	350	NDRT	340	0.40	241
						SCK CEN	350	UC	337	0.62	181
						SCK CEN	350	NDRT	372	0.38	276
						SCK CEN	350	UC	363	0.56	218
						SCK CEN	350	NDRT	395	0.45	278
						SCK CEN	350	UC	357	0.61	199

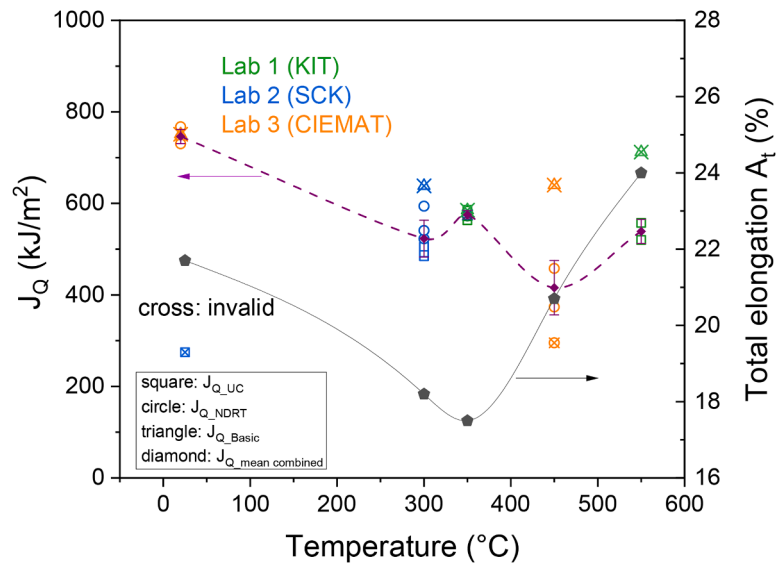


Fig. 6. Left Y-axis, bottom X-axis: Fracture toughness of ID48 plate as a function of temperature. Results obtained by different techniques are differentiated by different symbols and the results obtained by different labs are differentiated by different colors, see legend. The invalid data that were not taken into account for the analysis are shown by crossed symbols. The diamonds show results obtained by averaging relevant UC and NDRT data. Dashed line is a guide for the eye. Right Y-axis, bottom X-axis: Total elongation of batch 3 as a function of temperature [3].

investigation of the tensile and J - R curve behavior of ASME Grade 91 steel in a wide temperature range (toughness study between 300 and 600°C) in [33] revealed non-monotonic evolution of the crack resistance behavior with temperature, characterized by an inferior J - R curve at a test temperature of 400°C, which was correlated to a minimum in the tensile ductility. At intermediate temperatures a minimum in the fracture toughness has been also reported in [34] and [35], for P91 and SA516-Gr. 70 steels, respectively. On the base of the observed strain rate sensitivity, manifested by a shift of the temperature for fracture toughness minimum to higher temperatures with increasing the strain rate, DSA was considered to be responsible for the minimum in the fracture

toughness temperature dependence [35]. Taking these findings into account an increase of the toughness at 550°C for ID48 plate could be correlated to an increase of the tensile ductility. Overall, ID48 plate exhibits high toughness in the entire investigated temperature range. The fracture toughness is highest at RT but tends to decrease at high temperatures. An average toughness of above 500 kJ/m² measured at 300°C is well above the corresponding values for the batch 1 of EUROFER97 (EUROFER97-1) with a reported fracture toughness of 342 kJ/m² [12]. The reason for the superior fracture behavior of EUROFER97-3 as compared to EUROFER97-1 is not clear. The fracture mode, being characterized by formation of equiaxed dimples shown in

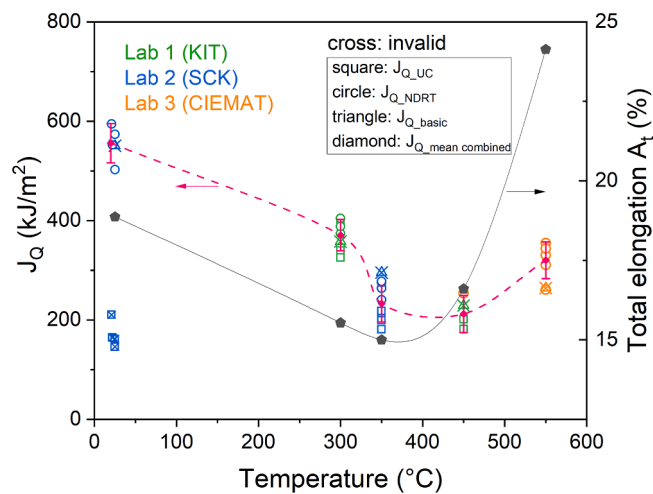


Fig. 7. Left Y-axis, bottom X-axis: Fracture toughness of ID70 plate as a function of temperature. Results obtained by different techniques are differentiated by different symbols and the results obtained by different labs are differentiated by different colors, see legend. The invalid data that were not taken into account for the analysis are shown by crossed symbols. The diamonds show results obtained by averaging relevant UC and NDRT data. Dashed line is a guide for the eye. Right Y-axis, bottom X-axis: Total elongation of batch 4 as a function of temperature [25].

Fig. 3 (b) resembles qualitatively to the one reported in [12] even though no direct quantitative comparison is possible. It is noteworthy to note that the two addressed batches exhibit rather similar behavior under uniaxial tensile loading and thus the differences in the toughness cannot be related to the differences in the tensile ductility properties. High fracture toughness measured on ID48 plate is beneficial for the material application in the in-vessel components of a fusion reactor.

Contrary to the ID48, the fracture toughness of ID70 plate shows less complex dependence on the temperature, see Fig. 7. The toughness is decreasing when the temperature is increased from RT to 350°C and exhibits a broad minimum between 350 and 450°C. The observed increase of the fracture toughness at 550°C is presumably related to the increase of tensile ductility of EUROFER97. The average value of toughness of 371 kJ/m² at 300°C is considerably lower than the corresponding value measured on ID48 plate and is close to the value reported on batch 1 of EUROFER97 in [12]. Overall, the fracture toughness of ID70 plate is still high enough for structural applications in the investigated temperature range. Comparison of ID48 and ID70 plates indicates that lower yield strength may be beneficial for the fracture toughness noting that this may not always be the case particularly when considering the behavior of batch 1 of EUROFER97 [12]. It is noteworthy that weak fracture toughness-strength relationship was concluded for ferritic martensitic steels in [36] after analyzing the datasets in the low and high temperature ranges. The current investigations do confirm that in the case of ferritic martensitic steels the tensile strength is not the only controlling parameter for the fracture toughness. Fracture toughness and crack growth resistance are more sensitive than tensile properties to local microstructural features, including the size and distribution of precipitates, the martensite lath/subgrain structure, the prior-austenite grain size, and the inclusion population. This is particularly important in ferritic/martensitic steels, where fracture is controlled by a small volume ahead of the crack tip that contains a complex hierarchical microstructure.

The results obtained on batch 3 and batch 4 of EUROFER97 will allow solid analysis of the dispersion of the fracture toughness between different industrial batches and will be used for closing gaps in the fracture toughness database, being a step forward for the codification of the material in the RCC-MRx code.

5. Summary

Fracture toughness and crack growth resistance behavior have been investigated for two batches of the European reference RAFM steel EUROFER97 at elevated temperatures. The crack resistance procedure by implying the UC technique was chosen as a default approach even though the NDRT and the BP of ASTM E1820 were also applied. The construction of the crack resistance curves at elevated temperatures appeared to be challenging requiring careful preparation and performance of the experiments. The main lessons learned from the current work are summarized as follows:

- Application of HT extensometers is challenging due to increased weight of the COD devices in combination with potential creep effects and stress relaxation. Reversals of the loading direction required for the application of the UC method may become a source of sliding of the extensometer knives thus introducing a scatter and/or offset into the signal resulting deterioration of the determined crack length. The apparent negative crack growth requires correction and may become an additional source in the uncertainty of measured toughness.
- Application of NDRT for the determination of the crack resistance curve was found to be successful particularly at lower temperatures. Getting rid of partial unloadings is recommended to avoid scattering of the extensometer signal which may lead to violation of the validity requirement on the normalized force displacement curve fit quality.
- Application of the BP is recommended when a testing of sufficient number of specimens is affordable. Availability of the datapoint close to 0.2 mm offset construction line appeared to reduce an error in the fracture toughness when the requirement on the number of the tested specimens could not be fulfilled.
- Lab-to-lab reproducibility studies need to be performed to minimize the uncertainty in the measured fracture-mechanical properties.

Both investigated plates showed very high fracture toughness with mean K_{I0} values of at least 297 MPa m^{0.5} for ID48 and at least 212 MPa m^{0.5} for ID70 well above the ductility limit of 100 MPa m^{0.5}. The crack growth resistance behavior is also very good in the entire investigated temperature range, even though the ID48 plate exhibited superior performance. Reduction of toughness with increasing the temperature is followed by an increase of the toughness which is attributed to the increase of the tensile ductility at elevated temperatures. Nucleation, growth and coalescence of micro-voids appears to be the dominant fracture mechanism in the entire temperature range. The fracture toughness of batch 3 and batch 4 is superior or at least comparable to that of batch 1. The results obtained in the current work will be used for closing gaps in the fracture toughness database on EUROFER97 and will be implemented for the codification of the material in RCC-MRx code.

CRediT authorship contribution statement

E. Gaganidze: Writing – original draft, Resources, Investigation, Formal analysis, Conceptualization, Funding acquisition. **D. Terentyev:** Writing – review & editing, Resources, Methodology, Investigation, Funding acquisition. **M. Serrano:** Writing – review & editing, Resources, Methodology, Investigation, Funding acquisition. **P. Lamagnère:** Writing – review & editing, Methodology. **M. Walter:** Writing – review & editing, Investigation. **T.T.M. Nguyen:** Investigation. **A. Zinovev:** Writing – review & editing, Methodology, Investigation. **D. Bermúdez Parra:** Writing – review & editing, Investigation. **G. Pintsuk:** Writing – review & editing. **G. Aiello:** Writing – review & editing. **M. Zmitko:** Writing – review & editing. **Y. Poitevin:** Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal

relationships which may be considered as potential competing interests: E. Gaganidze reports financial support was provided by European Union. D. Terentyev reports financial support was provided by European Union. M. Serrano reports financial support was provided by European Union. P. Lamagnere reports financial support was provided by European Union. M. Walter reports financial support was provided by European Union. T. T. M. Nguyen reports financial support was provided by European Union. A. Zinovev reports financial support was provided by European Union. D. Bermudez Parra reports financial support was provided by European Union. G. Pintsuk reports financial support was provided by European Union. G. Aiello reports financial support was provided by European Union. M. Zmitko reports financial support was provided by European Union. Y. Poitevin reports financial support was provided by European Union. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

This publication reflects the views only of the authors, and Fusion for Energy cannot be held responsible for any use which may be made of the information contained therein.

Data availability

The authors do not have permission to share data.

References

- [1] M. Zmitko, Y. Carin, N. Thomas, M. Simon-Perret, A. LiPuma, L. Forest, et al., The European ITER Test Blanket Modules: EUROFER97 material and TBM's fabrication technologies development and qualification, *Fusion Eng. Design* 124 (2017) 767–773.
- [2] G. Pintsuk, G. Aiello, S. Dudarev, M. Gorley, J. Henry, M. Richou, et al., Materials for in-vessel components, *Fusion Eng. Design* (2022) 112994.
- [3] RCC-MRx 2018 Edition, Design and Construction Rules for Mechanical Components of Nuclear Installations: High Temperature, Research and Fusion Reactors, AFCEN (2018).
- [4] T. Lebarbé, C. Pétesch, J. Muñoz-Garcia, Standardization of eurofer material, a first step toward industrialization, *Fusion Eng. Design* 159 (2020) 111793.
- [5] ASTM International, E1921-21a, Standard Test Method for Determination of Reference Temperature, T_0 , for Ferritic Steels in the Transition Range, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959. United States, 2021.
- [6] E. Lucon, R. Chaouadi, Marc Decretion, Mechanical properties of the European reference RAFM steel (EUROFER97) before and after irradiation at 300°C, *J. Nucl. Mater.* 329–333 (2004) 1078–1082. Vols.
- [7] J. Rensman, "NRG Irradiation Testing: Report on 300°C and 60°C Irradiated RAFM Steels," 2005.
- [8] N. Ilchuk, P. Stätig, G.R. Odette, Fracture toughness characterization in the lower transition of neutron irradiated EUROFER97 steel, *J. Nucl. Mater.* 442 (2013) S58–S61.
- [9] P. Fernandez, A.M. Lancha, J. Lapena, M. Serrano, M. Hernandez-Mayoral, Metallurgical properties of reduced activation martensitic steel Eurofer in the as-received condition and after thermal ageing, *J. Nucl. Mater.* 307–311 (2002) 495. Vols.
- [10] M. Serrano, P. Fernandez, J. Lapena, Fracture toughness evaluation of eurofer97 by testing small specimens, *ASTM Spec. Tech. Public.* 5 (2008) 114–121.
- [11] H.-C. Schneider, Entwicklung einer miniaturisierten bruchmechanischen Probe (2005).
- [12] R. Chaouadi, Effect of irradiation-induced plastic flow localization on ductile crack resistance behavior of a 9%Cr tempered martensitic steel, *J. Nucl. Mater.* 372 (2008) 379–390.
- [13] E. Gaganidze, J. Aktaa, Use of the failure assessment diagram to deduce ductile fracture toughness of the RAFM steel EUROFER97, *Int. J. Press. Vessels Piping* 86 (2009) 345–350.
- [14] M. Mahler, S. Fessi, J. Aktaa, Simplified approach for ductile fracture mechanics SSTT and its application to Eurofer97, *Nucl. Mater. Energy* 26 (2021).
- [15] ASTM International, E1820-18a, standard test method for measurement of fracture toughness, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959. United States, 2018.
- [16] International Standard, ISO 12135 - 2021, Metallic materials - Unified method of test for the determination of quasistatic fracture toughness.
- [17] C.-S. Seok, Correction methods of an apparent negative crack growth phenomenon, *Int. J. Fract.* 102 (2000) 259–269.
- [18] K. Weiss, A. Nyilas, Specific aspects on crack advance during J-test method for structural materials at cryogenic temperatures, *Fatig. Fract. Eng. Mater. Struct.* 29 (2005) 83–92.
- [19] Y.A. Rosenthal, R.L. Tobler, P.T. Purtscher, Data Analysis methods with a 'negative crack growth' correction procedure, *J. Test. Evalu.* 18 (1990) 301–304.
- [20] E. Lucon, Review and consideration of apparent negative crack growth in fracture toughness tests, *Mater. Perform. Characteriz.* (2024).
- [21] X. Chen, R.K. Nanstad, M.A. Sokolov, J–R curve determination for disk-shaped compact specimens based on the normalization method and the direct current potential drop technique, *Small Spec. Test Techniq.*, ASTM STP 1576 6 (2014).
- [22] J. Dzugan, H.-W. Viehrig, Application of the normalization method for the determination of J–R curves, *Mater. Sci. Eng. A* 387–389 (2004) 307–311. Vols.
- [23] H. Ernst, P.C. Paris, M. Rossow, J.W. Hutchinson, Analysis of load-displacement relationship to determine J-R curve and tearing instability material properties, *Blacksburg* (1979) 581–599. ASTM STP 677.
- [24] Saarschmiede GmbH Freiformschmiede, "https://www.saarschmiede.de/", Bismarckstraße 57-59, 66333 Völklingen.
- [25] A. Zinovev, C.-C. Chang, J. Van Eyken, E. Gaganidze, D. Terentyev, Effect of neutron irradiation to 0.7 dpa and 1.4 dpa on the tensile properties and fracture surface of EUROFER97 steel, *J. Nucl. Mater.* 587 (2023) 154742.
- [26] Epsilon technology corp, Jackson, WY USA, "www.epsilontech.com," [Online].
- [27] J.D. Landes, J calculation from front face displacement measurement on a compact specimen, *Int. J. Fract.* 16 (1980) R183.
- [28] D. Terentyev, P. Lamagnère, Y. Lejeail, G. Perez, M. Walter, T. T. M. Nguyen, et al., "Qualification of EUROFER97 and design rule validation for ITER TBM: EUROfusion contribution," *J. Nucl. Mater.*, submitted manuscript 2026.
- [29] J. Vanaja, K. Laha, S. Sam, M. Nandagopal, S. Panneer Selvi, M.D. Mathew, T. Jayakumar, E. Rajendra Kumar, Influence of strain rate and temperature on tensile properties and flow behaviour of a reduced activation ferritic-martensitic steel, *J. Nucl. Mater.* 424 (2012) 116–122.
- [30] J. Varghese, K.V. Rajulapati, K. Bhanu Sankara Rao, S.D. Meshram, G.M. Reddy, Ambient, elevated temperature tensile properties and origin of strengthening in friction stir welded 6 mm thick reduced activation ferritic-martensitic steel plates in as-welded and post-weld normalised conditions, *Mater. Sci. Eng. A* 857 (2022) 144019.
- [31] Z. Xu, Y. Shen, Serrated flow and work-hardening behavior of China low activation martensitic steel (CLAM), *Metals* 8 (2018) 413. Vols.
- [32] A.F. Armas, M. Avalos, I. Alvarez-Armas, C. Petersen, R. Schmitt, Dynamic strain ageing evidences during low cycle fatigue deformation in ferritic-martensitic stainless steels, *J. Nucl. Mater.* 258–263 (1998) 1204–1208. Vols.
- [33] H.-Y. Lee, -W D, J.-Y. Jeong Lim, Effects of long-time service at high temperature on the material strength and J-R curve of Grade 91 steel, *Eng. Fract. Mech.* 178 (2017) 445–456.
- [34] B. Shashank Dutt, M. Nani Babu, S. Venugopal, G. Sasikala, A.K. Bhaduri, Effect of test temperature on fracture toughness of modified 9Cr–1Mo steel, *Mater. Sci. Technol.* 27 (2011) 1527.
- [35] J.H. Yoon, B.S. Lee, Y.J. Oh, J.H. Hong, Effects of loading rate and temperature on J–R fracture resistance of an SA516-Gr.70 steel for nuclear piping, *Int. J. Press. Vessels Piping* 76 (1999) 663–670.
- [36] T.S. Byun, D.T. Hoelzer, J.H. Kim, S.A. Maloy, A comparative assessment of the fracture toughness behavior of ferritic-martensitic steels and nanostructured ferritic alloys, *J. Nucl. Mater.* 484 (2017) 157–167.