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Master curve evaluation of ANP-5 steel using mini-CT specimens

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Abstract

The nuclear industry demands analyses that make possible the long-term operation of nuclear power plants (i.e., beyond 40 years). In this sense, one of the main challenges to overcome is the restricted amount of material available to extend the surveillance programs. To mitigate this issue, mini-CT specimens have been proposed for the evaluation of the fracture properties of reactor pressure vessel (RPV) materials, and particularly, the corresponding Master Curve. These specimens can be taken from the broken halves of previously tested Charpy specimens. In this work, mini-CT specimens have been employed to evaluate the reference temperature of the RPV ANP-5 steel in non-irradiated conditions. The results were compared with those obtained by means of conventional fracture tests.

Keywords:

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1. Introduction

The monitoring of the reactor pressure vessel (RPV) materials is an indispensable prerequisite for the safe operation of nuclear power plants (NPPs). RPVs are usually made of bainitic ferritic steels which tend to become increasingly brittle when subjected to neutron irradiation. Moreover, this irradiation also leads to an increase in the ductile-to-brittle transition temperature and therefore the long-term monitoring of these materials is essential. Surveillance programmes are based on the observation of changes in the mechanical properties of structural materials that limit

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structural integrity and, thus, service life. The test data obtained from these programmes provide an early estimate of any degradation of the mechanical properties. In this context, the availability of material for testing is limited, so the applicability of miniature CT specimens is of great interest. For example, one tested Charpy specimen allows the fabrication of eight mini-CT specimens.

Moreover, the Master Curve (MC) approach for assessing the fracture toughness of an irradiated reactor pressure vessel (RPV) steel has gained acceptance throughout the world. This direct measurement approach is preferred over the correlative and indirect methods used in the past (e.g., Charpy tests) to assess irradiated RPV integrity. The MC was originally proposed by Wallin (Wallin, 1984), and the approach has been standardised through ASTM E1921 (ASTM International, 2021). This standard allows the use of undersized specimens in the determination of the transition temperature, T_0.

Recently, the applicability of mini-CT specimens within the MC approach has been intensively studied with unirradiated base materials (Chaouadi et al., 2016; Miura and Soneda, 2010; Yamamoto et al., 2014) and weld metals (Sokolov, 2018; Yamamoto and Miura, 2016), as well as with irradiated materials (Ha et al., 2018; Server et al., 2018; Uytdenhouwen and Chaouadi, 2020). However, the production and testing of mini-CT specimens are still subject to a number of uncertainties, especially when dealing with irradiated materials, and these uncertainties need to be resolved before these procedures can be accepted by the different standards and regulations. To develop the production and testing technology, and to validate the results obtained with mini-CT samples, the European research project FRACTESUS was initiated in 2020 (Brynk et al., 2021; Cicero et al., 2020), providing the framework of the present research.

This paper aims to provide further validation of using mini-CT specimens made of an RPV weld material to define the corresponding Master Curve. Thus, Section 2 presents the materials and methods. Section 3 gathers the experimental results and provides the evaluation of the T_0, together with an analysis of the observed micromechanisms and the corresponding discussion. Finally, Section 4 presents the main conclusions.

2. Materials and Methods

2.1. Materials

In this study, a modified NiCrMo1 weld metal (ANP-5) was investigated in baseline conditions. This material belonged to an RPV test weldment and is representative of the RPV weldments of the 1st generation of German pressurized water reactors (PWRs). The ANP-5 material was fully characterised in the previous project CARISMA (Hein et al., 2010). The chemical composition and some mechanical properties are presented in Table 1 and Table 2, respectively. This material was provided by Framatome as a broken crack arrest specimen (see Figure 1a), from which 19 mini-CT specimens were extracted. The dimensions of the mini-CT specimens are shown in Figure 1b.

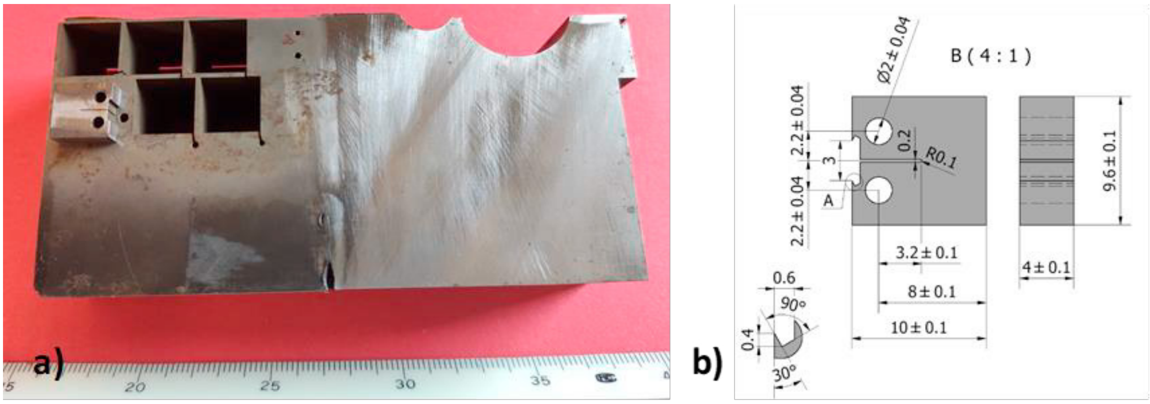

Figure 1. a) Extraction of mini-CT specimen from the original broken CT specimen; b) geometry of the mini-CT specimen used in this study (dimensions in mm).

Table 1. Chemical composition (wt. %) of ANP-5 steel.

C	Si	Mn	P	S	Cr	Mo	Ni	Cu
0.08	0.15	1.14	0.015	0.013	0.74	0.60	1.11	0.22

Table 2. Mechanical properties of ANP-5 steel.

σ_{yRT} (MPa)	σ_{uRT} (MPa)	T_{68J} (°C)	T_{41J} (°C)	RT_{NDT} (°C)	T_0 (ºC)
604	696	0	-12	-28	-38

2.2. Methods

The reference temperature (T_0) of the ANP-5 steel was determined by applying the Master Curve (MC) approach to a mini-CT specimen. This fracture characterisation tool enables the fracture toughness of ferritic steels to be estimated within the ductile to brittle transition zone (DBTZ). According to the MC, the fracture toughness dependency on temperature as well as the scatter of the results can be described by a statistical model and a single parameter, the reference temperature (T_0). This represents the temperature at which the median fracture toughness is equal to 100 MPa√m. Therefore, the MC may be defined for any probability of failure once T_0 is determined. The location of the median fracture toughness $K_{JC\,(med)}$ is based on T_0, following the equation:

$$K_{JC(med)} = 30 + 70 \cdot \exp[0.019 \cdot (T - T_0)] \tag{1}$$

In addition, this approach takes into consideration the statistical effect of the specimen thickness on fracture toughness. Thus, according to the MC, when testing specimens with a thickness other than 1T (25.4 mm), the obtained K_{JC} values should be translated into the equivalent K_{JC} for 1T ($K_{JC(1T)}$), as suggested by equation (2):

$$K_{JC(1T)} = 20 + [K_{JC} - 20]\left(\frac{B}{25.4}\right)^{1/4} \tag{2}$$

The fracture characterisation of this RPV steel in the DBTZ has been determined by the MC methodology and, thus, following the guidelines provided by ASTM E1921 (ASTM International, 2021).

The tests were conducted using a servo-hydraulic testing machine with a load capacity of 100 kN. The specimens were loaded by monotonic displacement control with a loading rate of 1 MPa√m/s, which is in accordance with ASTM E1921. In order to determine the T_0, the tests were performed at low temperatures (-88 to -56 ºC), which was achieved by injecting liquid nitrogen into an environmental chamber. A crack opening displacement extensometer (COD) was attached to the front face of the specimen. Therefore, once the tests were completed, the measured displacements were corrected to the load line.

3. Results and discussion

Two specimens exceeded the stable crack growth allowed by ASTM E1921 (0.2 mm) and the values were censored. Even though it is censored, the data still contain statistically usable information and can be considered as censored data by replacing the violated K_{JC} value with the maximum uncensored K_{JC} value of the entire dataset. In addition, all specimens met the requirements for both pre-crack length and straightness according to ASTM E1921.

The size-corrected, valid and censored values were used to calculate T_0 with the master curve analysis. A valid T_0 of -26.1 °C was obtained for the ANP-5 with a standard deviation of 6.7 °C. Figure 2 shows the experimental data, before censoring, and the resulting master curve, with the 5% and 95% confidence limits. Figure 2 also shows the validity window of the master curve. It can be observed that three values were discarded from the analysis for being outside of the allowed temperature range of ± 50ºC. Here, it is important to point out the reduced validity windows when dealing with miniaturized specimens, since the $K_{JC(limit)}$ is proportional to the remaining ligament. In this sense, to obtain a sufficient number of uncensored values it is recommended to carry out the tests at temperatures lower than the reference temperature.

As the main conclusion, the difference between the T_0 values obtained with mini-CT specimens and with ordinary CT specimens was +11.9ºC (a positive value implies that T_0 was higher when using mini-CT specimens). This variability is consistent and in the same range as the results that can be found in the literature.

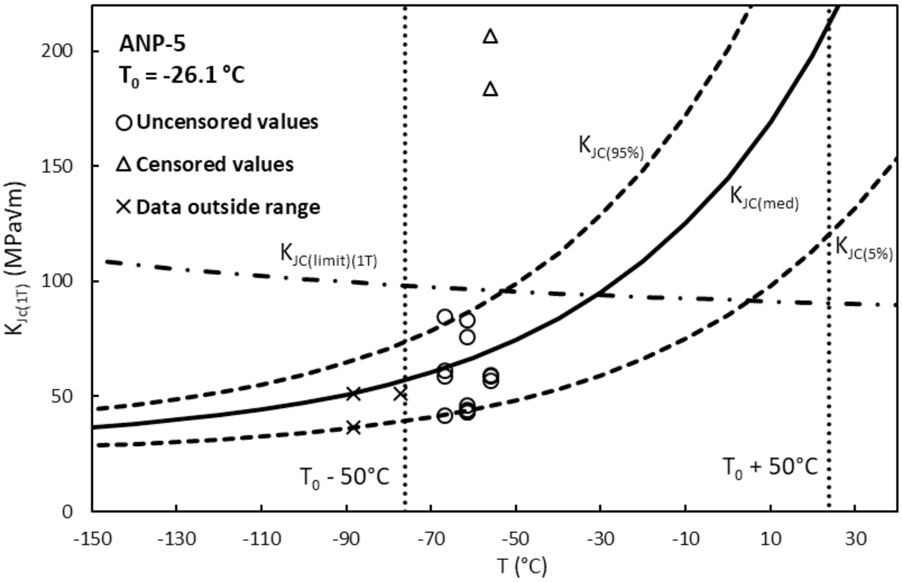

Figure 2. Master Curve analysis of ANP-5 material.

4. Fractography

In order to demonstrate the applicability of mini-CT specimens with the MC approach, all the broken specimens were analysed with a scanning electron microscope (SEM). Figure 3 shows an example.

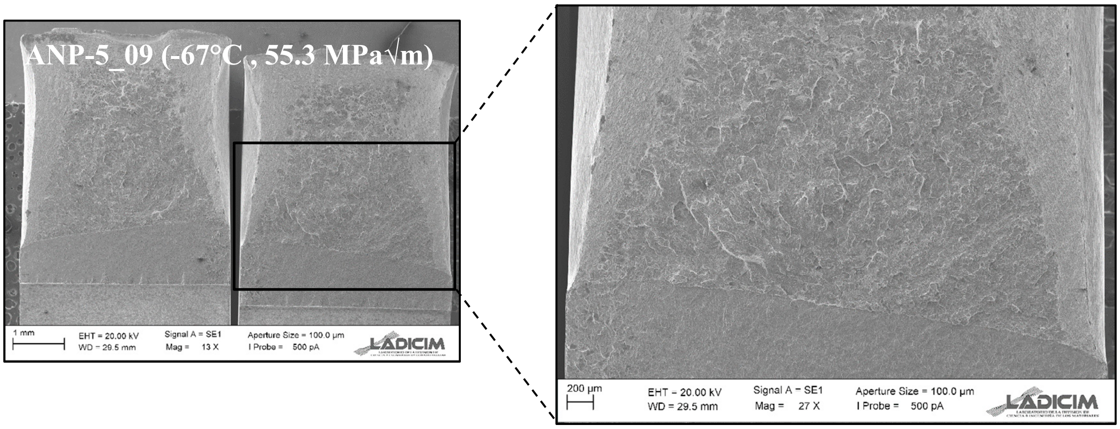

Figure 3. Example of the fracture surface of an ANP-5 specimen.

After a minimum ductile front, a large flat area can be observed where the main micromechanism is cleavage fracture. In addition, one clear dominant area of initiation may be detected in the middle of the specimen, which is shown with more magnification in Figure 4. This is the expected behaviour in the DBTZ assumed by the MC approach since the initiation from triggering particles following the weakest link mechanism is the governing process. Another important observation is the appearance of two areas on the edges of the specimen. This slant fracture is likely an effect of the plane stress state on the sides of the specimen.

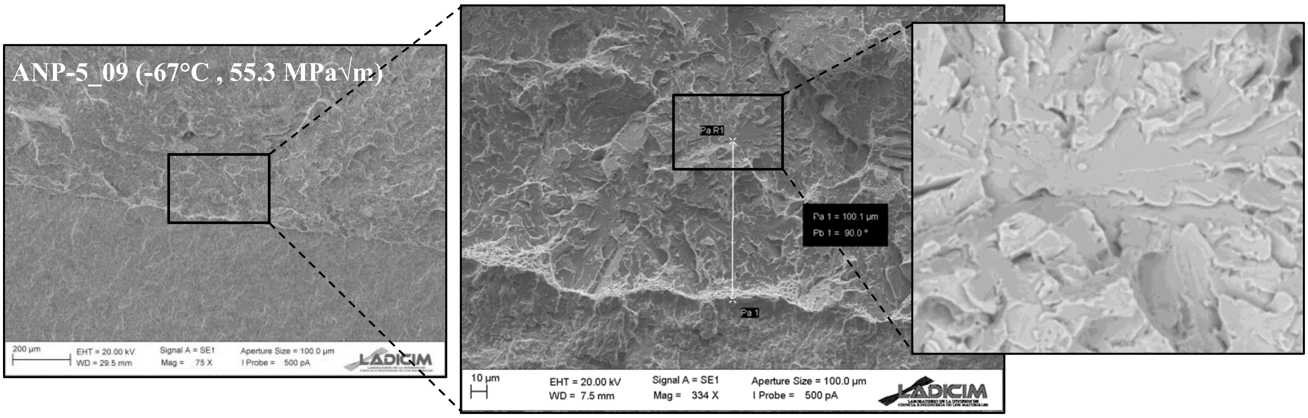

Figure 4. Example of a location of the initiation site.

5. Conclusions

In this paper, mini-CT specimens and the Master Curve approach have been applied to characterise the behaviour of a reactor pressure vessel (RPV) weld steel (ANP-5) within the ductile-to-brittle transition zone (DBTZ). This paper confirms the suitability of mini-CT specimens for the characterisation of the DBTZ (T_0) of RPV weld materials. As the main output, the reference temperature (T_0) was successfully obtained from the fracture toughness tests performed on mini-CT specimens, being consistent with the T_0 obtained from standard specimens (-26.1ºC vs. -38ºC). In addition, the fractographic analysis confirms that the main micromechanism found in the mini-CT specimens was cleavage fracture from a (main) single initiation point, thus following the weakest link model assumptions. With all this, the use of this miniaturised testing technique in combination with the Master Curve approach allows the fracture evaluation of the DBTZ to be performed with reduced volumes of material.

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