International Journal of Pressure Vessels and Piping 135-136 (2015) 36–51

Contents lists available at ScienceDirect

International Journal of Pressure Vessels and Piping

journal homepage: www.elsevier.com/locate/ijpvp

# Fracture mechanics characterisation of reactor pressure vessel multi-layer weld metal

H.-W. Viehrig [a, *], M. Houska [a], D. Kalkhof [b], H.-J. Schindler [c]

[a] Helmholz-Zentrum Dresden-Rossendorf, P.O.Box 510119, 01314 Dresden, Germany
[b] Swiss Federal Nuclear Safety Inspectorate (ENSI), Switzerland
[c] Mat-Tec AG, Winterthur, Switzerland

ARTICLE INFO

*Article history:*
Received 29 November 2013
Received in revised form
9 October 2015
Accepted 20 October 2015
Available online 22 October 2015

*Keywords:*
Reactor pressure vessel
Multi-layer welding seam
Specimen orientation
Fracture toughness
Master curve approach
Reference temperature

ABSTRACT

The multi-layer beltline welding seam of the Biblis C reactor pressure vessel was characterized by hardness, tensile, ISO-V impact and fracture toughness testing. The reference temperature, $T_0$, was determined according to the test standard ASTM E1921 at different thickness positions of the multi-layer welding seam. Additionally, the influence of the specimen orientation on the ISO-V ductile-to-brittle transition temperature and $T_0$ was investigated. In contrast to the T-S orientation (crack extension through the thickness) the crack front of the T-L oriented specimens (crack extension in welding direction) penetrates several welding beads. By means of fractographic and metallographic analyses of the fractured surface of fracture mechanics SE(B) specimens was shown that the distribution of the crack initiation sites is not necessarily correlated to the structure of the different welding beads along the crack front. Furthermore, it was found that the scatter of the fracture toughness values at cleavage failure, $K_{Jc}$, determined with T-S specimens is significantly higher than in case of the T-L specimens. $T_0$ values measured at different thickness locations of the multi-layer welding seam vary in a range of about 40 K.

The evaluated $T_0$ values are used to determine the reference temperature $RT_{To}$ for indexing the lower bound curve $K_{Ic}(T)$ according to the Regulatory Guide ENSI-B01 for the ageing surveillance of nuclear power plants in Switzerland. It could be shown that the $K_{Ic}$ values converted from the $K_{Jc}$ values are enveloped by the lower bound curves.



## 1. Introduction

There are two common methods to determine fracture toughness of ferritic reactor pressure vessels steels in the ductile-to-brittle transition regime: The lower bound $K_{Ic}(T)$-curve based on the nil-ductility temperature $RT_{NDT}$ according to the ASME code [1], which is well suited for deterministic analysis, and the Master-Curve (MC) approach [2,3], providing statistical tolerance bounds. Actually, the former is empirically developed for RPV-steels, so it is formally restricted to this type of steels. However, as shown in Ref. [4], it can be generalized to the same family of structural steels that is covered by ASTM E1921 [2]. Within the MC-concept, fracture toughness is characterized by the reference temperature $T_0$ that has to be determined according to ASTM E1921 [2]. For RPV steels it has been shown empirically that $RT_{NDT}$ and $T_0$ are related to each other by $RT_{NDT} = T_0 + 19.4$ K [5]. In the Regulatory Guide ENSI-B01 [6] for the ageing surveillance of nuclear power plants in Switzerland this relation is used to determine the lower bound curve $K_{Ic}(T)$. Since $T_0$ is known to be affected by measurement uncertainties and biases depending on specimen type [2] and test temperature [7], in ENSI-B01 [6] the above relation is extended by an additional temperature shift that accounts for these effects by an adequate margin of safety.

The ENSI-Guide [6] is applicable not only to the base metal of the RPV, but also to its welds. In the latter case some additional aspects need to be considered. Firstly, in a multi-layer submerged welding seam the mechanical properties are expected to vary across the thickness. Secondly, the micro-structure is inhomogeneous by segregations and other metallurgical effects in each weld bead, which are likely to increase the scatter of $K_{Jc}$ and, consequently, the measurement uncertainty of $T_0$. Thirdly, the weld material behaves anisotropic, particularly with respect to fracture toughness. Besides, concerning the experimental evaluation of $T_0$, the question

* Corresponding author.
*E-mail address:* h.w.viehrig@hzdr.de (H.-W. Viehrig).

http://dx.doi.org/10.1016/j.ijpvp.2015.10.002
0308-0161/

**Nomenclature**

| | |
|---|---|
| ART | reference temperature adjusted on the irradiation status |
| $b_0$ | specimen ligament |
| $B_{p\varepsilon}$ | thickness required to fulfil the plane-strain condition according to ASTM E399 [22]. |
| C(T) | compact tension specimen |
| DBTT | Ductile-to-brittle transition temperature |
| E | Young's modulus |
| ENSI | Swiss Federal Nuclear Safety Inspectorate |
| ISO-V | impact specimen with an notch radius of 0.25 mm according to ISO 148-1 [15]. |
| $K_{IC}$ | plain-strain fracture toughness |
| $K_{Jc}$ | fracture toughness measured at cleavage failure of the specimen |
| $K_{Jc(limit)}$ | Specimen size and constraint validity limit in ASTM E1921 [2]. |
| $K_{Jc(1T)}$ | fracture toughness measured at cleavage failure of the specimen with thickness adjusted to 1T according to ASTM E1921 [2]. |
| KTA | Nuclear Safety Standards Commission, Germany |
| $KV_2$ | impact energy determined according to ISO 148-1 [15] with a striker radius of 2 mm |
| M | deformation limit in $K_{Jc(limit)}$ set on 30 in ASTM E1921 [2]. |
| MC | Master Curve |
| MM | multi modal MC based approach |
| N | total number of the tested specimens |
| NDT | nil ductility temperature measured with the drop weight test |
| $n_i$ | weighting factor per specimen, as a function of $T_i-T_0$; values span from 1/6 to 1/8 |
| r | number of valid $K_{Jc}$ values according to the size criterion in ASTM E1921 [2]. |
| RPV | reactor pressure vessel |
| $RT_{NDT}$ | reference temperature derived from the NDT and verified with Charpy-V results |
| $RT_{ref}$ | reference temperature for the $K_{Jc}$ (T) reference curve acc. to ENSI-B01 [6]. |
| SE(B) | single edge bend specimen |
| SEM | scanning electron microscope |
| SINTAP | Structural Integrity Assessment Procedures for European Industry |
| $TT_{41J}$ | ductile-to-brittle transition temperature related to $KV_2 = 41$ J determined by tangent hyperbolic fitting |
| $TT_{41J}^{upper}$ | ductile-to-brittle transition temperature related to $KV_2 = 41$ J determined by the upper threshold line |
| $T_0$ | reference temperature according to ASTM E1921 [2]. |
| $TT_0^{MM}$ | reference temperature evaluated according to the multi modal Master Curve approach [8–10]. |
| 1T | 1 inch (25.4 mm) |
| UBL | upper bound line of the impact energies $KV_2$ |
| 0.4T | 0.4 inch (10 mm) |
| ν | Poisson's ratio |
| σ | standard deviation |
| $\sigma_{ys}$ | yield strength |

arises whether or not ASTM E1921 [2] is applicable at all, since there is a statement that non-uniform materials such as multi-layer welds are not amenable to the underlying statistics. According to ASTM E1921 [2] attention should be paid to the 2% and 98% tolerance bounds: size adjusted $K_{Jc(1T)}$-data falling outside this band may indicate inhomogeneous material. Anyway, if the two approaches mentioned above are applied to welds, then the inhomogeneity of the material is obviously an issue and its effect on $T_0$ needs to be considered. The MC based multi modal and the SINTAP approaches are suitable for the evaluation of $K_{Jc(1T)}$ data sets measured on specimens of inhomogeneous materials [8–10]. These evaluation approaches provide a reference temperature which is representative for the brittle fraction (SINTAP) and the continuous distribution of $K_{Jc(1T)}$ values (multi modal) of the material to be assessed. The multi modal MC approach has been applied on the datasets investigated in this paper.

In the ENSI-guideline [6] the uncertainty associated with weld metals is accounted for by an additional margin $\Delta T_M$. To validate this procedure and to clarify some of the questions raised above, ENSI funded the present investigation. As a representative test material, two segments from the multi-layer beltline welding seam of the Biblis C RPV were available. Biblis C is a German NPP which was never commissioned, its already manufactured RPV is being used then for test and studying purposes. $T_0$ is determined as a function of the thickness-position by means of pre-cracked Charpy size specimens (0.4T-SE(B)). For comparison, also a number of C(T) specimens are tested. It is expected that the loading direction and specimen orientation will affect $T_0$ as well as its scatter. Depending on the orientation of the specimens, the welding bead structure is different along their fatigue crack front. In specimens with T-S orientation (specimen axis axial and crack extension through the thickness) the fatigue crack front is located in one welding bead with a uniform structure. On the contrary, the fatigue crack front of the T-L oriented specimens (specimen axis axial and crack extension in welding direction) penetrates several welding beads with a non-uniform structure [11]. Therefore, the two crack orientations T-S and T-L applied in RPV surveillance programmes are compared to each other. Additionally, ISO-V impact specimens of both orientations were tested for comparison.

## 2. Test material and specimens

The investigations were performed on the multi-layer beltline welding seam between the upper and lower ring of the Biblis C RPV (Fig. 1). The original submerged arc weld was removed due to quality defects. The welding seam was completely renewed using a filler wire S 3 NiMo1 (Ø 5 mm). Table 1 contains the chemical composition and Fig. 2 [12] shows the drawing and a macrograph of the investigated beltline multi-layer welding seam.

Two RPV segments, 220 AB S and 220 AD3 S, containing the welding seam and base metal from the upper and lower forged rings were available (Fig. 1). Whereas the segment 220 AB S (Fig. 3) contains the whole thickness of the RPV wall, the segment 220 AD3 S (Fig. 4) was straightened by cutting a thickness of 30 mm on both sides. As shown in Fig. 3, the segment 220 AB S was cut into 29 sheets. From each sheet 25 Charpy size SE(B) specimens (0.4T-SE(B)) were machined over the thickness of the multi-layer welding seam, so that in total 29 specimens result from every thickness location. From the rest of the material, tensile specimens were manufactured. A minimum number of 10 T-L and T-S oriented 0.4T-SE(B) specimens were machined from each thickness location. From the segment 220 AD3 S, ISO-V and 1T-C(T) specimens were machined (Fig. 4). The ISO-V specimens were machined in a similar manner like the 0.4T-SE(B) specimens, whereby the thickness