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# Variability and Lower Bound of Fracture Toughness of Welds in the Ductile to Brittle transition regime

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**Abstract**

The reference temperature $T_0$ was measured for both T-S and T-L- specimen orientation in 24 layers across the thickness of the beltline weld of a reactor pressure vessel. It turned out to vary in a bandwidth of more than 40K. Because of a high scatter, no clear pattern of $T_0$ as a function of the thickness position could be recognized. A more detailed analysis revealed that the median of $K_{Jc}$ was considerably steeper than predicted by the Master-Curve, which leads to a bias of $T_0$ with respect to the test-temperature relative to $T_0$. By a modified evaluation procedure, the scatter of the reference temperature could be significantly reduced, which enabled the global pattern of $T_0$ to be recognized. By comparing the theoretical lower bound to $K_{Jc}$-data of the used specimens with the individual measured $K_{Jc}$ a representative $T_0$ that characterizes the overall toughness behaviour of the weld was determined. It turned out to be about 10 K lower than the maximum local $T_0$.


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## 1. Introduction

In the ductile to brittle transition (DTB) regime of ferritic steels the scatter of fracture toughness is one of the key issues in fracture mechanics. There are two well known concepts to cope with it: One is the probabilistic approach

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based on the Master-Curve (MC) suggested by Wallin (1995), the other the lower bound according to the ASME reference curve (ASME (2004)). The former is based on the observation that the median of $K_{Jc}$ of standard 1T-specimens follows a unique curve given by

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

where $T_0$ is the reference-temperature according to ASTM E1921 (2012). The ASME reference curve

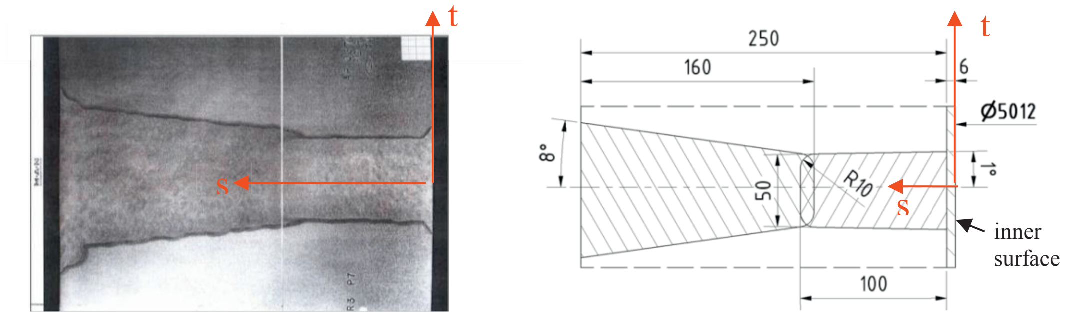
$$K_{Jc/med} = 36.5 + 22.8 \cdot \exp\left[0.036 \cdot (T - T_0 - 19.4K)\right] \tag{2}$$

was found as an empirical lower envelope of numerous valid $K_{Ic}$-values of RPV-steels (ASME (1999)).

In case of inhomogeneous materials, the situation is more complex. There is an increased scatter in the individual $K_{Jc}$-data of a test series, which increases the measurement uncertainty of $T_0$. As pointed out by Kalkhof and Schindler (2012) another source of uncertainty of $T_0$ may be the shape of the median of $K_{Jc(1T)}(T)$. The latter may be significantly steeper than predicted by (1), depending on the loading rate, specimen size and possibly the material. This effect increases the measurement uncertainty. It can be minimized by testing at temperatures close to $T_0$. However, in case of inhomogeneous material, testing close to $T_0$ is hardly achievable because of the variability of $K_{Jc}$ and $T_0$. These issues are dealt with in the present paper experimentally and theoretically. Furthermore, the relation between local $T_0$ and the lower bound of $K_{Jc}(T)$ in case of weld material is explored.

## 2. Experimental program and results

A detailed documentation of the testing procedure and experimental results can be found in Viehrig et al (2013, 2014), so we restrict ourselves here to a brief overview. As a representative test material, the beltline welding seam of the RPV of the non-commissioned reactor Biblis C was used. Fig. 1 shows a macrograph and the corresponding dimensions. From two segments of this weld, numerous pre-cracked Charpy size specimens (0.4T SEB) and a few 1T-CT-specimens are machined (Fig. 2). The aim was to determine $T_0$ as a function of s (distance from inner surface), which means that series of 10 – 20 specimens of equal thickness position (s) were machined and tested in separate data-sets. Both the T-L and the T-S crack orientations were considered. The microstructural inhomogeneity along the crack-front differs between these two crack orientations (Fig. 2).




(a) (b)

Fig. 1: Macrograph (a) and dimensions of the weld (b)

The distribution of $T_0$ determined by the 0.4T-SEB specimens according to ASTM E1921 is shown in Fig. 3. The loading rate was 1.2 $MPa \cdot m^{0.5}/s$, thus within the range of quasi-static testing according to ASTM E1921. Apparently, there is a rather random variation of $T_0$ for both specimen orientations T-L and T-S. The span between maximum and minimum $T_0$ is about the same for both orientations T-L and T-S, although the inhomogeneity along the crack front is different (see Fig. 2). The apparent variation or scatter results not only from the material inhomogeneity but also from the measurement uncertainty, as shown in the following.

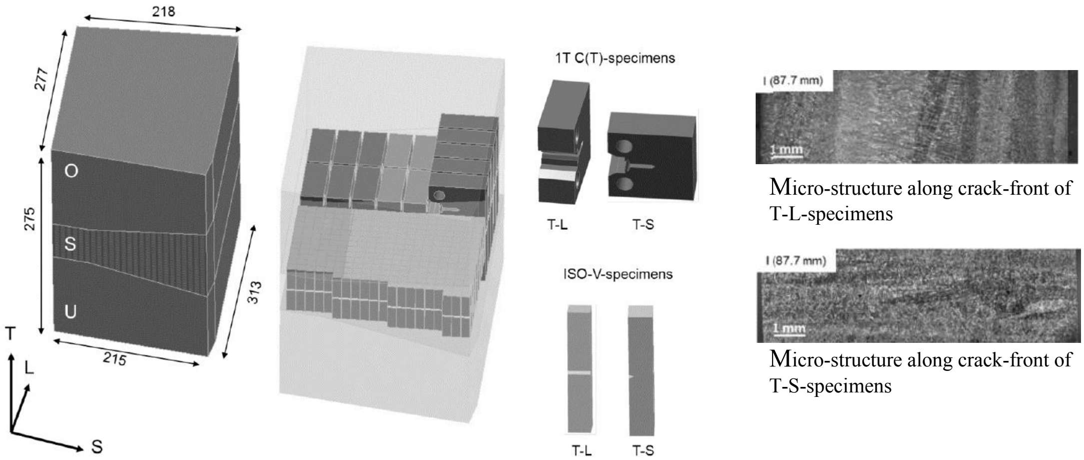



Fig. 2: Specimen removal from weld segment of the Biblis C RPV, and examples of microstructure along the crack front

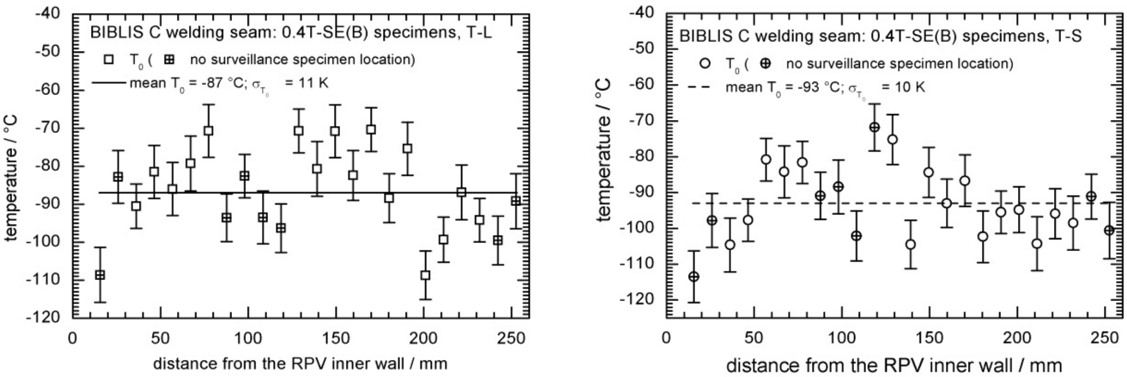



Fig. 3: Distribution of $T_0$ across the thickness along the s-axis for T-L (left) and T-S orientation (right) (from Viehrig et al. (2014)).

## 3. Evaluation of reference temperature $T_{100}$

As mentioned in the introduction the actual median $K_{Jc/med}(T)$ sometimes deviates from (1), which causes a bias in $T_0$ with respect to the testing temperatures, thus increasing the measurement uncertainty. In order to explore its effect on the apparent scatter of $T_0$, the $K_{Jc}$-data were evaluated for comparison by the OEF-method as suggested by Schindler and Kalkhof (2013, 2014). It is based on the more general assumption that the median is described by

$$K_{Jc/med(1T)} = 30 + 70 \cdot \exp\left[p \cdot (T - T_{100})\right] \tag{3}$$

Obviously, $T_{100}$ is identical with $T_{0,}$ if p = 0.019, but deviates from $T_0$ if p deviates from 0.019 and if the test temperature $T_{test}$ deviates from $T_0$. In these cases, $T_{100}$ is expected to be more precise than $T_0$. It is evident from eq. (3) that the exponent p can be determined from a set of experimental $K_{Jc(1T)}$ as the slope of the linear regression in the diagram ln($K_{Jc(1T)}$-30) vs. T. Applied to the $K_{Jc}$ measured by the 0.4T-SEB specimens, p turned out to exhibit a relatively large scatter, which is not surprising regarding the inhomogeneity of the material and the narrow temperature range covered in each data-set. However, the vast majority of p was clearly beyond the nominal value of 0.019. For physical reasons, p has to be the same for all test series, so the simple average of the individual values are supposed to be the best estimate. The following mean values are obtained for the two considered orientations:

T-L-orientation: $p_{av} = 0.032$ (4a)

T-S-orientation: $p_{av} = 0.039$ (4b)

With p fixed to $p = p_{av}$ eqs. (4a) and (4b) leads to the following simple equation to determine $T_{100}$ from a data-set of N $K_{Jc(1T)}$-values:

$$T_{100} = \frac{1}{N} \cdot \sum_{i=1}^{N} \frac{1}{p_{av}} \cdot \left[4.2485 + p_{av} \cdot T_{test(i)} - \ln\left(K_{Jc(1T)(i)} - 30\right)\right] \tag{5}$$

The resulting $T_{100}$ are shown in Fig. 4 in comparison with $T_0$ from Fig. 3. Note that at some thickness positions additional tests are performed at a single temperature. The two data-sets were evaluated separately, so two values of $T_0$ and $T_{100}$, respectively, appear at the same s, whereas in Fig. 4 all data are evaluated in combination as one data-set. Apparently, the scatter of $T_{100}$ is significantly reduced, compared with the one of $T_0$, and enables the general trend of the reference temperature as a function of s to be recognized much clearer than from Fig. 3.

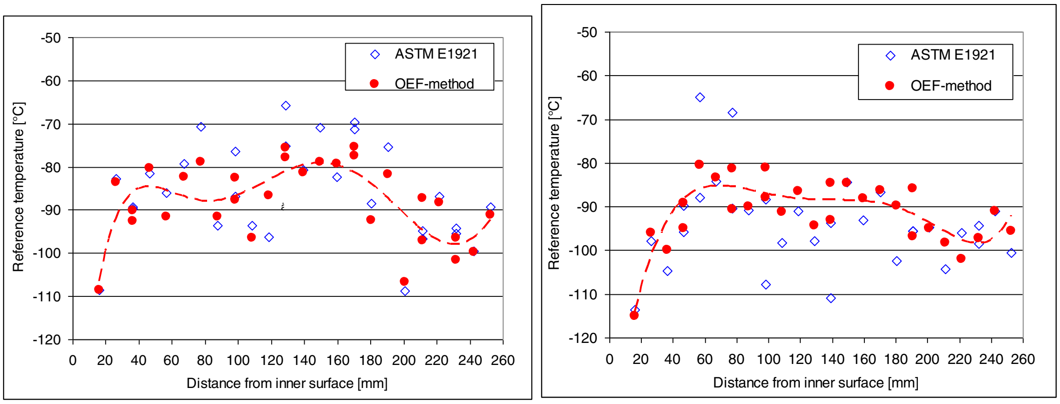



Fig. 4: Distribution of $T_{100}$ in comparison with $T_0$ from T-L-specimens (a) and T-S-specimen (b) across the thickness along the s-axis

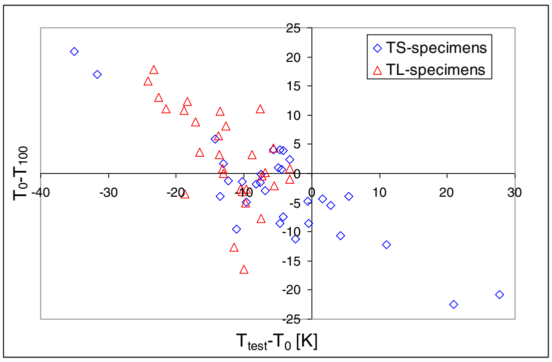



Fig. 5: Dependence of the difference $T_0$ - $T_{100}$ from the relative test temperature.

For the T-S-orientation, the standard deviation of the $T_{100}$ values from the general trend shown as the dashed lines is 4.2 K, which is less than the basic (unavoidable) measurement uncertainty as given in ASTM E1921. This means, that the microstructure does not significantly affect the scatter of $T_{100}$. For T-L orientation, the standard deviation is 6.1K, thus significantly higher, which can be explained by the more pronounced inhomogeneity of the microstructure along the crack-front (see Fig. 2). For $T_0$ the corresponding standard deviations are 8.2 K for T-L and 8.8 K for T-S, thus clearly higher.

Considering the relatively high $p=p_{av}$ values given by eqs. (4) there is no doubt that the procedure of ASTM E1921 leads to errors depending on the relative mean test temperature, $T_{test}$–$T_0$. Particularly in the case of inhomogeneous materials, $T_0$ is not known a priori, so $T_{test}$–$T_0$ is stochastic and its effect on $T_0$ contributes to the measurement uncertainty. Fig. 5 shows the difference between $T_0$ and $T_{100}$ in function of $T_{test}$–$T_0$. The trend is clear and corresponds to the temperature-induced bias that is expected on theoretical grounds. Particularly the extreme outliers are clearly associated with a relatively large $T_{test}–T_0$.

## 4. Lower bound of $K_{Jc}$

In a deterministic fracture mechanics analysis $T_0$ serves to quantify the lower bound of $K_{Ic}$ by means of (2). In the following the corresponding relation is explored for welds. Lacking experimental valid $K_{Ic}$, the corresponding comparison has to be done based on the measured $K_{Jc}$-data. For this purpose, the lower bound (2) and (3) has to be corrected for the limited thickness B of the used specimens. Schindler and Kalkhof (2013, 2013a) derived the following simple equation to correct (2) for thicknesses B smaller than the one required for plane strain conditions, $B_{sat}$:

$$K_{Jc}(B,T) = \frac{1.257}{B^{0.25} \cdot \sqrt{R_p(T)}} \cdot K_{Ic}^{3/2}(T) \quad for \quad B < B_{sat} = \frac{2.5 \cdot K_{Jc}^2}{R_p^2} \tag{6}$$

with $R_p$ denoting the yield stress. For $B>B_{sat}$, $K_{Jc} = K_{Ic}$. Though much simpler, eq. (6) is in good agreement with the approach of Merkle et al. (2002). For homogeneous materials, (6) with $K_{Jc}$ from (2) was demonstrated to represent a rather tight (i.e. realistic) lower bound to experimental $K_{Jc}$ (Schindler and Kalkhof, (2013), (2013a)). In reverse, as elaborated by Schindler (2014), it is even possible to estimate $T_0$ by fitting $K_{Jc}$ to the theoretical scatter-band formed by (6) and (2).

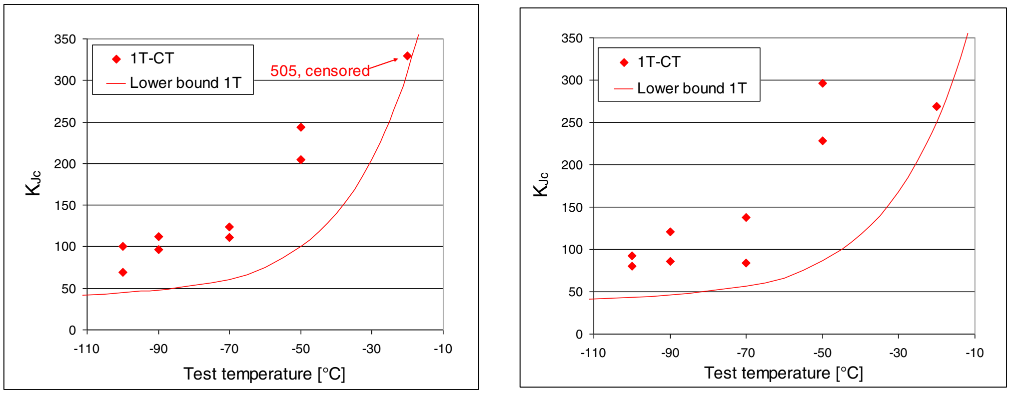



Fig. 6: Experimental $K_{Jc}$ measured by using 1T-CT-specimens in comparison with eq. (6) with B=0.0254 m and $T_0$ = -91°C for T-L-specimens (left) and $T_0$ = -87°C for T-S-specimens (right). The value for T-L at -20°C was measured to be $K_{Jc}$ = 505 $MPam^{0.5}$, thus beyond the validity limit, so it was censored according to ASTM E1921.

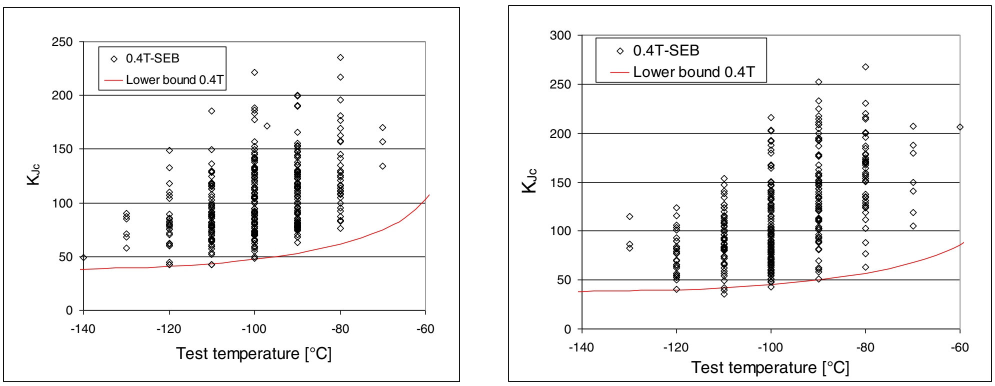



Fig. 7: Experimental $K_{Jc}$ measured by using 0.4T-SEB-specimens in comparison with eq. (6) with B=0.01 and $T_0$ = -91°C for T-L-specimens (left) and $T_0$ = -87°C for T-S-specimens (right)

The 1T-CT specimens are expected to reflect the overall toughness behaviour of the weld better than the small 0.4T SEB specimens. In Fig. 6 the experimental $K_{Jc}$ obtained from 1T-CT-specimens taken randomly from the weld are shown. The envelopes shown in Fig. 6 are obtained from (6) and (2) by inserting B=0.0254m and $T_0$= -91°C for the T-L-orientation, and $T_0$= -87°C for the T-S-orientation, respectively. The same $T_0$ with B = 0.01m delivers the theoretical lower bounds of $K_{Jc}$ for 0.4T-SEB-specimens. In fact, as shown in Fig. 7, it envelops practically all relevant $K_{Jc}$ measured on the 0.4T-SEB-specimens, which is another verification of eq. (6). This means that the corresponding $T_0$ = -91°C and -87°C for T-L and T-S, respectively, can be regarded as physically representative $T_0$-values. Note that they are relatively close to the average values of $T_0$ as given in Fig. 3

## 5. Conclusions

The reference temperature $T_0$ of the considered beltline weld of an RPV varies in a bandwidth of more than 40 K across the thickness. The variation is due not only to the inhomogeneity of the material, but – to a substantial part - also to the uncertainty of the standard measurement procedure of $T_0$. The uncertainty is increased by more than 20K, compared to homogeneous materials. The main reason for the increased scatter was found to be the slope of the median $K_{Jc}(T)$ of the 0.4T-SEB specimens (pre-cracked Charpy specimens), which is significantly steeper than predicted by the MC. This means that the procedure according to ASTM E1921 is biased by the relative test temperature $T_{test}$–$T_0$. The error introduced by the choice of the test temperatures can be as large as ±20 K, even if the testing close to $T_0$ is strived for. It has to be accounted for by an extra safety margin.

Previous investigations on homogeneous material indicated that the exponent p depends on the loading rate and specimen size, so the effect of the test temperatures on $T_0$ may be different at different loading rates. Therefore it is recommended to check the slope of the MC. If the coefficient p of the exponent deviates significantly from 0.019, then the suggested OEF-method delivers improved, less scattering reference temperatures $T_{100}$.

The lower envelope of the individual $K_{Jc}$-values was found to correspond to a characteristic reference temperature that is close to the average $T_0$, thus considerably lower than the maximum $T_0$. This means that finding the maximum local $T_0$ is not necessary to characterize the overall toughness behaviour of the weld. The average $T_0$ as determined by a data-set from arbitrary positions in the weld plus some adequate safety margin is sufficient.

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