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The impact of different ways of measuring the notch dimension in the CRB test

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SHORT SUMMARY

The Cracked Round Bar (CRB) test, which is standardised in ISO 18489, evaluates the long-term failure resistance of thermoplastic pipe materials to slow crack growth (SCG). The standard is currently being revised to emphasise factors including accurate measurement of the notch depth, which is crucial to properly assess the actual stress applied to samples. This paper discusses challenges faced when measuring notch depth in thermoplastic materials and highlights how small discrepancies have a major impact on the actual stress, and as a direct consequence also on the end result. Standardised notch measurement protocols are essential to produce consistent and reliable results. The findings show the importance of precise measurements to accurately determine the resistance of materials to crack initiation and growth.

KEYWORDS

Cracked round bar test, CRB, notch, cross section, polyethylene

ABSTRACT

The Cracked Round Bar (CRB) test was developed and standardised in ISO 18489 as a means of characterising the long-term failure resistance of thermoplastic pipe materials to slow crack growth (SCG). The standard is currently under revision. One of the issues being discussed is how to measure the actual notch depth to allow the actual stress applied to the sample to be evaluated. This paper discusses the practical challenges faced when measuring the notch depth after the CRB test with PE 100-RC. Precise notch measurement is crucial, as it directly affects the actual applied stress and the resulting stress intensity factor (K), which leads to different fracture behaviour. Small discrepancies in measurements of the notch depth can cause the resistance to crack growth of the material to be misrepresented. The findings underscore the necessity of standardised notch measurement protocols to ensure consistency and reliability when testing resistance to slow crack growth.

Identifying the exact onset of the transition remains challenging due to the subjective nature of data interpretation. One promising indicator is the fluid velocity at the trailing edge of the notch and in particular the speed at the very tip of the cut, which may signal the beginning of the transition. To improve accuracy during notching, additional factors should be considered/re-evaluated, including the shape of the knife, the pressure applied during notching and thermal influences.

INTRODUCTION

The cracked round bar (CRB) test method (ISO 18489 [1]) is used to evaluate the resistance of thermoplastic materials commonly employed in piping systems to slow crack growth under cyclical loading conditions [1, 2, 3]. With this method, four cylindrical specimens are notched using a razor blade and subjected to various stress levels. The number of cycles to failure is recorded for each stress level. This typically results in a straight line when plotted on a double logarithmic scale. This allows for the assessment of the response of the material to varying stress levels as indicated by the slope of the line, which can differ between materials. However, in practice, a more common approach is to perform a single point interpolation at a stress level of 12.5 MPa. This enables a comparative ranking of different thermoplastic materials based on the number of cycles to failure (N_f). The product standards [4, 5] for PE piping systems (water and gas) state that a material must withstand 1.5 million cycles at 12.5 MPa to meet the pass/fail criterium for PE 100-RC.

Round robin testing [6] carried out in 2023 revealed that the current test standard lacks a clear and consistent procedure for measuring the initial crack length in CRB specimens. Participating laboratories employed different methods, which led to variability in the results. Accurate measurement of the initial crack length is very important, because the actual initial crack length always differs (slightly) from the target initial crack length. Because this measurement can only be taken after specimen failure, the applied stress must be corrected to reflect the actual conditions experienced during testing. In other words, the actual stress intensity factor at the notch tip differs from the target value, and this discrepancy must be accounted for to ensure reliable and comparable test results.

This paper describes different methods of determining the initial crack length. This is one of the largest contributors to the total measurement uncertainty. The basis for the estimated measurement uncertainty is demonstrated with the help of accumulated quality control data. The paper includes a measurement study of repeatability, interlaboratory reproducibility and different operators.

The paper clearly demonstrates the necessity of determining the initial crack length in a uniform way. This will contribute to the development of the ISO test standards and is expected to reduce interlaboratory scatter.

EXPERIMENTAL

ISO 18489 [1] states that test specimens should be notched with a razor blade to the target initial crack length (a_{ini}*). For PE specimens, this is 1.50 mm in the current version of the standard. A schematic cross section of a CRB test specimen is shown on the left of figure 1. Note that the target initial crack length (indicated with an asterisk on the left of figure 1) and diameter (D) of the test specimen determine the target initial ligament diameter (D_{ini}*). This can be expressed with the formula:

$$D_{ini}^{*} = D - 2 \cdot a_{ini}^{*} \qquad (1)$$

The target initial ligament diameter[1] can be used to calculate the test load based on the preferred (target) stress level ($\Delta\sigma_0$*) and the load ratio (R):

$$F_{max} = \frac{{D_{ini}^{*}}^{2} \cdot \pi \cdot \Delta\sigma_0^{*}}{4 \cdot (1 - R)} \qquad (2a)$$

[1] Note that the formula in this paper is different from the formula in ISO 18489:2015. In this paper, D_{ini}* has an asterisk, while in the standard D_{ini} is given without an asterisk. Since the actual initial ligament diameter is unknown at this point, only the target initial ligament diameter – the version with an asterisk – is correct. This will be corrected in the new version of ISO 18489.

And as:

$$\Delta F = F_{max} - F_{min} \tag{2b}$$

$$F_{min} = F_{max} \cdot R \tag{2c}$$

It follows that:

$$\Delta F = \frac{{D_{ini}^{*}}^{2} \cdot \pi \cdot \Delta\sigma_0^{*}}{4} \tag{2d}$$

Once the test specimen fails due to dynamic loading, the actual initial crack length (a_{ini} without an asterisk) can be determined using an optical microscope with suitable image processing software that allows dimensions to be measured. An actual cross section of a failed test specimen is shown on the right of figure 1. The dashed yellow semicircle indicates the transition between the two distinct surface textures: the razor-sharpened notch and the fatigue crack initiated from the notch. By determining a_{ini}, the actual stress level can be calculated using formula 3.

$$\Delta\sigma_0 = \frac{4 \cdot \Delta F}{(D - 2a_{ini})^2 \cdot \pi} \tag{3}$$

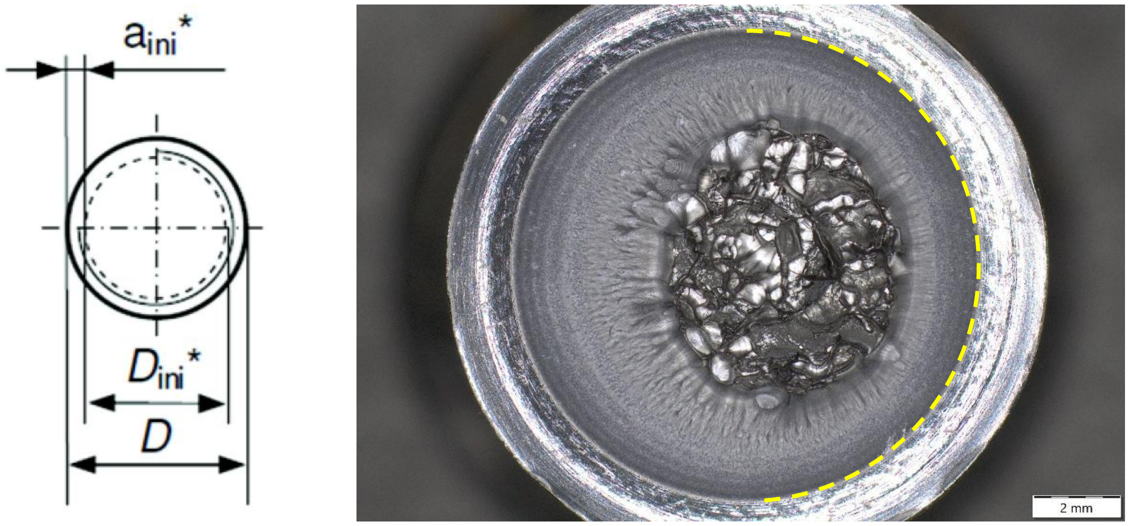


Figure 1. Left: the cross section of a CRB test sample shown schematically in ISO 18489 [1]. Right: an actual cross section of a tested PE specimen (photo taken with an optical microscope). The dashed yellow semicircle indicates the difference in surface texture between the razor notch and fatigue crack.

There are three ways to determine the (actual) initial crack length after failure:
- By measuring a_{ini}
- By measuring D_{ini}
- By measuring A_{ini} (actual ligament area)

The three measurement methods are explained below.

Measuring a_{ini}

This method seems to be suggested by ISO 18489:2015, which states that:
[…] *the initial crack length,* a_{ini}*, shall be measured after completion of the cyclic test by analysing the created fracture surface.*

This method appears to be straightforward: a_{ini} is measured from the edge of the specimen to the end of the notch (see figure 2). However, this approach has two key drawbacks:

1. *Low accuracy due to single measurements*: ISO 18489 does not specify how many measurements to take. Due to surface irregularities, a single measurement is unreliable.
2. *Systematic overestimation*: during notching, the thermoplastic material deforms outwards to form a small rim (see figure 3). This rim increases the diameter of the specimen at the notch. When viewed under a microscope, it is mistakenly included in the measurement of a_{ini}. This leads to consistent overestimation, regardless of measurement precision or repetition. Since a_{ini} is small, even minor errors can significantly affect results.

To address these issues, the actual ligament diameter of the fracture surface should be measured after the test. The true a_{ini} can then be calculated using the same principle as in formula (1).

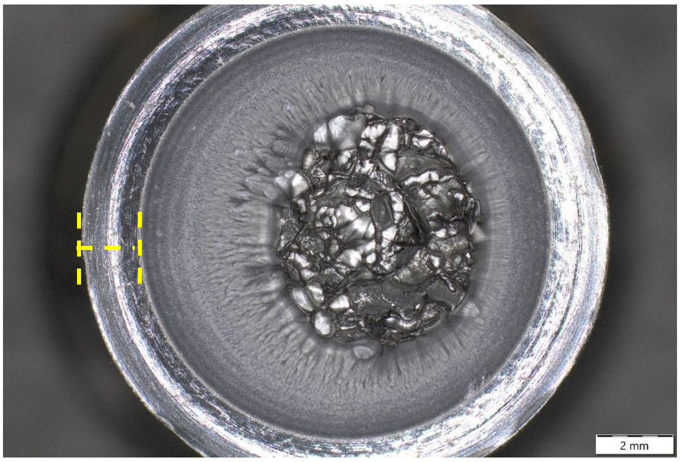


Figure 2. The method of measuring a_{ini} directly.

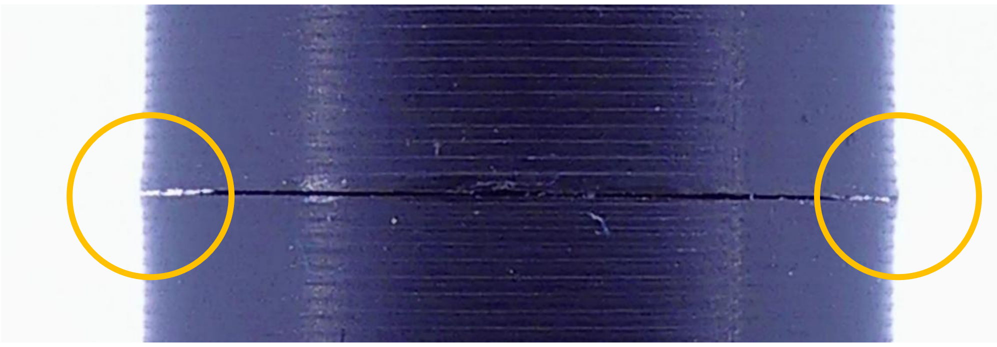


Figure 3. PE material will flow out as a result of the notching process (orange circles). This creates a small rim directly next to the notch.

Measuring D_{ini}

To determine D_{ini}, a straight line is drawn across the fracture surface from one side of the notch transition to the other (see figure 4). This line represents the initial ligament diameter D_{ini}. However, accurately drawing this line is challenging because it must pass through the exact centre of the circular fracture surface. If it does not, the measured diameter will be underestimated (see figure 5).

By drawing multiple lines, the centre becomes more apparent. This allows reasonably accurate measurements to be made. The measured diameter can be used to calculate a_{ini} using formula (1), which is now based on the actual notch depth rather than the target notch depth. These values can subsequently be used to determine the actual stress level using formula (3).

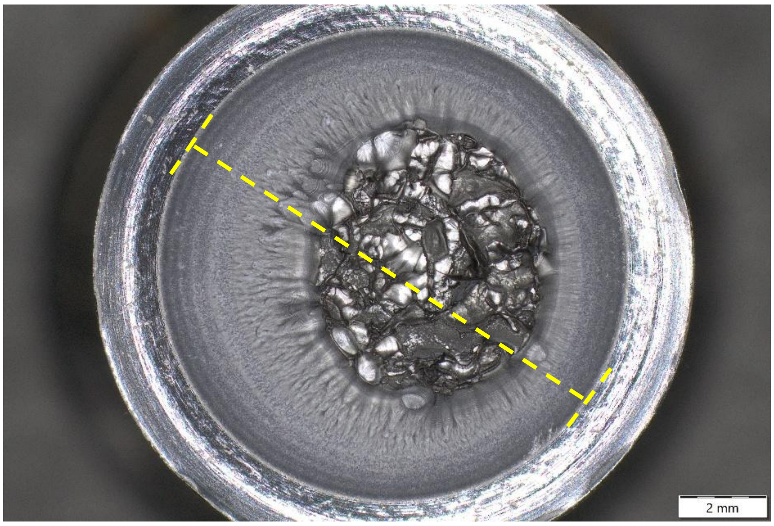


Figure 4. The method of measuring D_{ini} directly.

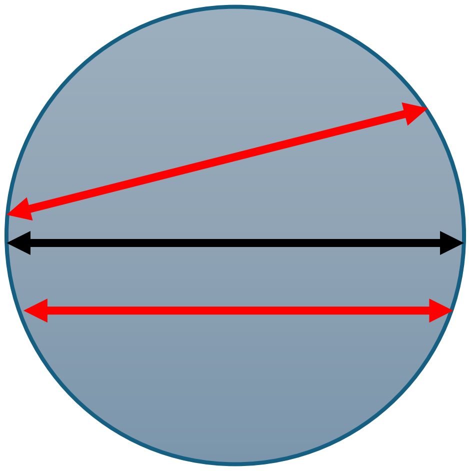


Figure 5. The difficulty of measuring D_{ini} directly. The correct diameter is only obtained if the measurement is made through the exact centre of the circle (black arrow). In all other cases the measured diameter will be too small (red arrows).

Measuring A_{ini}

With this method, a circle is fitted by selecting three points along the notch transition (see figure 6). Image processing software is then used to determine the initial unnotched surface area (A_{ini}), which can be used directly to calculate $\Delta\sigma_0$:

$$A_{ini} = \pi \cdot \left(\frac{D_{ini}}{2}\right)^2 = \pi \cdot \frac{D_{ini}^2}{4} \tag{4}$$

Combining this with formula (1):

$$(D - a_{ini})^2 = \frac{4 \cdot A_{ini}}{\pi} \tag{5}$$

Results in the actual stress calculation, formula (3):

$$\Delta\sigma_0 = \frac{\Delta F}{A_{ini}} \tag{6}$$

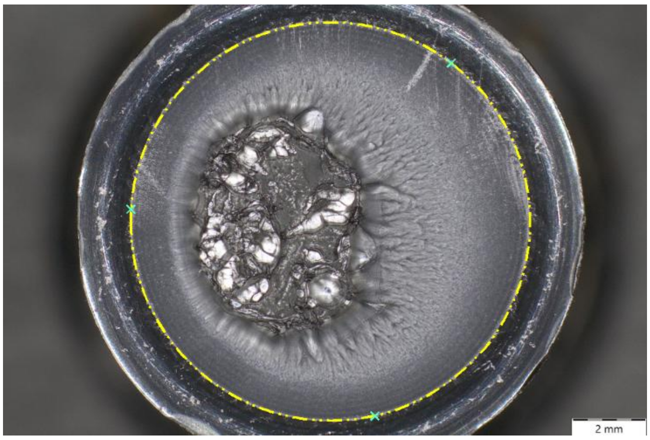
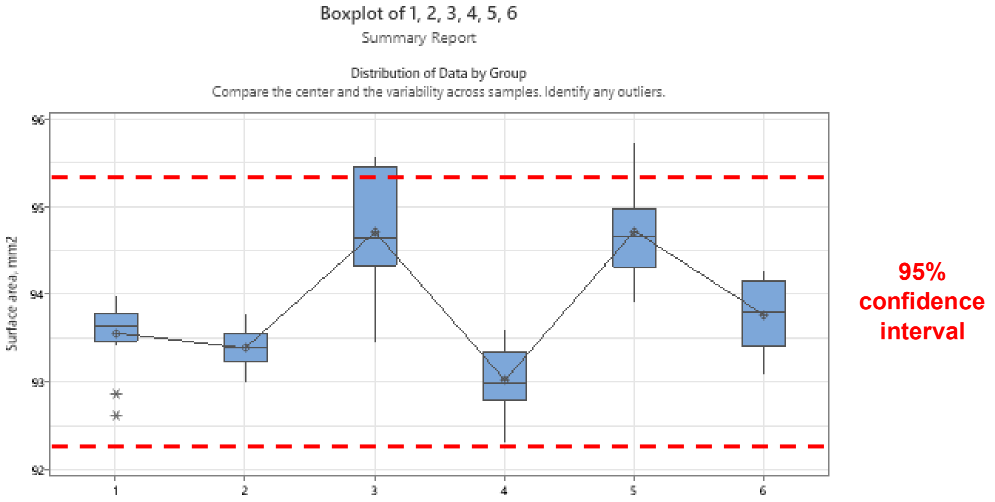


Figure 6. The method of measuring A_{ini} using a circle.

While fitting a circle through three points is convenient, it has limitations, as the ligament is rarely a perfect circle. A more accurate approach would involve selecting multiple points along the transition and using image processing software to generate a best-fit circle.

UNCERTAINTY CALCULATIONS

To determine the uncertainty of the measurement of the surface, the area was measured eight times on one side of the test specimen and eight times on the other side by six different analysts, two of whom were very experienced (analysts 1 and 2) in analysing the surface area. A total of 96 (= 2 x 8 x 6) measurements were made of the fractured ligament surface area of one test specimen. The results of the measurements are shown in figure 7 as a box and whisker plot, which shows the minimum value (lowest whisker), first quartile (lower part of the box), median (line in the box), mean or average (diamond in the box), third quartile (upper part of the box) and maximum value (top whisker) of a data set.



Statistics	1	2	3	4	5	6
N	16	16	16	16	16	16
Mean	93.548	93.38	94.701	93.011	94.715	93.753
StDev	0.35452	0.23163	0.66843	0.35862	0.50804	0.39380
Minimum	92.61	92.98	93.44	92.29	93.9	93.08
Maximum	93.97	93.76	95.57	93.6	95.72	94.26

Figure 7. Box and whisker plot (Minitab® 22.2.2) of a total of 2x8 measurements (top and bottom) of the surface area of one test specimen carried out by six analysts. The red dashed lines represent the margins of the 95% confidence interval (see figure 8).

This plot shows that even measuring the same surface area results in considerable scatter. It is also clear that different analysts make significantly different measurements. Although there is a clear distinction between the razor-sharpened notch and the fatigue crack initiated from the notch, determining where exactly the transition begins is still subjective. This is probably due to a transition in the actual notching and turning the lathe freely without further progress of the razor blade at the end of the notch (just before removing the razor blade from the specimen). Even though the razor blade runs freely at the end of the notch, it is not unlikely that the notch will become slightly deeper in some locations. For less experienced analysts, this first transition may seem to be the end of the notch, while in fact the notch continues slightly further. This will result in overestimations by some of the analysts. Clear instructions and training analysts are therefore crucial.

The average value of all the measurements is 93.85 mm^2 (standard deviation 0.78 mm^2) with a 95% confidence interval of 0.16 mm^2 (determined with the help of the 1-sample T hypothesis test), which means it can be stated with 95% confidence that the average value lies between 93.69 mm^2 (average minus confidence interval) and 94.01 mm^2 (average plus confidence interval). The histogram of the data is shown in figure 8 below.

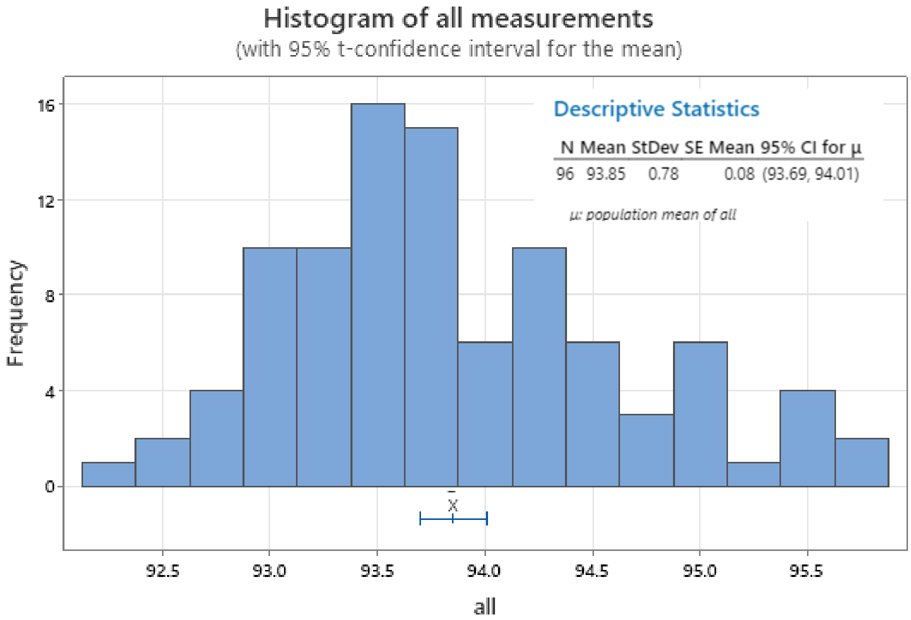


Figure 8. Histogram plot of all measurements (top and bottom) of the surface area of one test specimen by six analysts (Minitab® 22.2.2).

However, in normal practice each test specimen will never be measured 96 times. *What value may an analyst obtain from just one measurement?* Assuming 95% certainty, this value will lie between twice the standard deviation of all measurements below the average and twice the standard deviation above the average. As the standard deviation is 0.78 mm^2, twice the standard deviation is 1.56 mm^2. It can thus be said with 95% certainty that the analyst will obtain values between 92.29 mm^2 and 95.41 mm^2, as indicated with red dashed lines in figure 7.

What does this mean? The test specimen should be perfectly round with a diameter of 14.00 mm and a notch (initial crack length) with a depth of 1.50 mm. For a stress level $\Delta\sigma_0$* of 11.5 MPa, this would result in a ΔF of 1093 N (formula (2d)). With an average actual ligament area of 93.85 mm^2 after failure, this results in an actual initial crack length of 1.53 mm (assuming that the actual diameter of the test specimen is 14.00 mm). Although the target stress level $\Delta\sigma_0$* is 11.5 MPa, the actual stress level $\Delta\sigma_0$ is thus 11.6 MPa (formula (6))[2]. However, depending on the measurement made by the analyst (between 92.29 mm^2 and 95.41 mm^2, see the red dashed lines in figure 7), the actual stress level $\Delta\sigma_0$ may vary between 11.4 MPa and 11.8 MPa!

The failure time of four test specimens is normally measured and the values interpolated to produce a single stress level. To see how this error in measuring the surface area determines the final interpolated value, a fictitious slope is assumed. The failure times are also chosen in such a way that the interpolated value is 1.5x10^6 cycles to failure at $\Delta\sigma_0$ = 12.5 MPa. This value is exactly equal to the requirement for PE 100-RC in the current product standards [4, 5] for PE piping systems (for water and gas). The results are given in table 1 and presented graphically in figure 9.

[2] Note that this value does not include the recalculation to an initial crack length of 1.40 mm as required in some of the PE product standards (e.g. EN 12201-1:2024)

Table 1. Example of CRB test results. ΔF is calculated using formula (1) and (2d) with test specimens with D = 14.00 mm and a_{ini}^* = 1.50 mm. $\Delta\sigma_0$, $\Delta\sigma_{0,low}$ and $\Delta\sigma_{0,high}$ are calculated with formula (6) using A_{ini} = 93.85 mm², 95.41 mm² and 92.29 mm² respectively.

$\Delta\sigma_0^*$ (MPa)	ΔF (N)	$\Delta\sigma_0$ (MPa)	$\Delta\sigma_{0,low}$ (MPa)	$\Delta\sigma_{0,high}$ (MPa)
11.5	1093	11.6	11.4	11.8
12.2	1159	12.4	12.2	12.6
12.8	1216	13.0	12.7	13.2
13.5	1283	13.7	13.4	13.9
a_{ini}		1.53	1.49	1.58
Interpolated number of cycles to failure at 12.5 MPa		**1.5x10⁶**	**1.4x10⁶**	**1.6x10⁶**

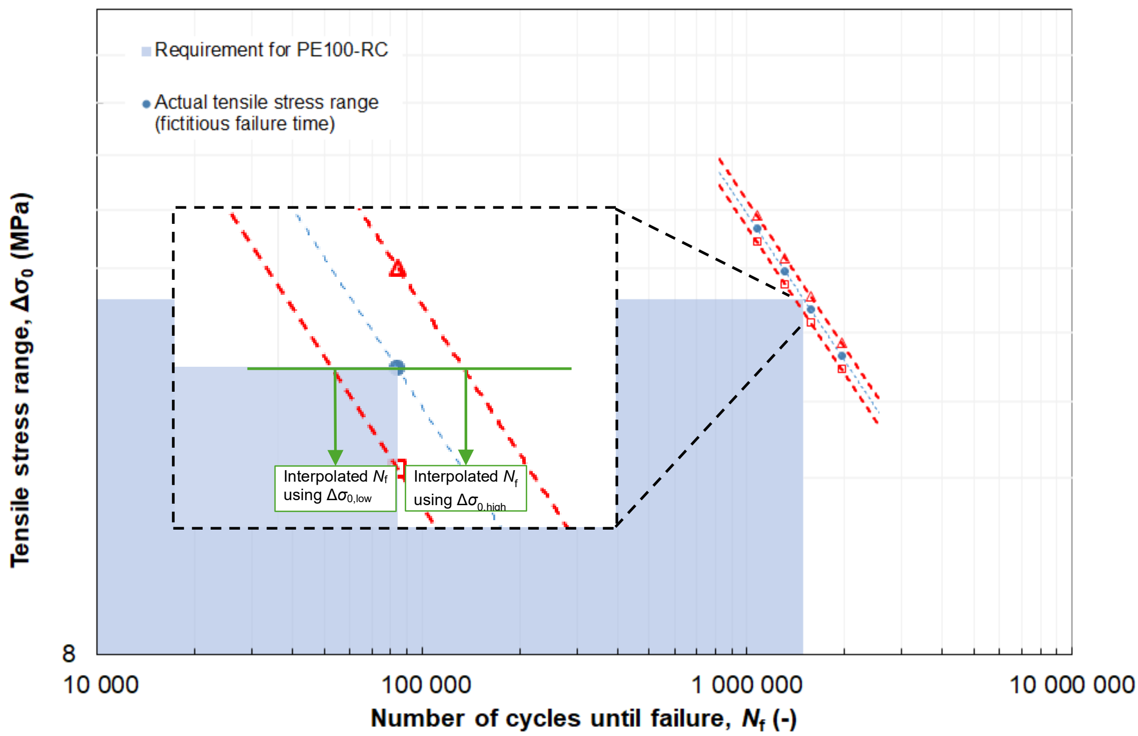


Figure 9. Difference in tensile stress range ($\Delta\sigma_0$) due to differences in the measured fracture surface area (A_{ini}), including the requirement specified in the product standard [4, 5]. The interpolated number of cycles to failure at 12.5 MPa ranges from 1.4x10⁶ to 1.6x10⁶ cycles. See table 1 for the values.

Note that the variation in the interpolated number of cycles to failure is highly dependent on the actual slope of the measuring data. However, this example does show the significance of differences in the measurements of the ligament diameter, which in this fictitious case results in an interpolated number of cycles to failure that is 6% higher or lower ($1.6x10^6$ or $1.4x10^6$ compared to $1.5x10^6$ cycles). This is an important parameter and needs to be measured very accurately. For comparison, the load cell is required to have an accuracy of ±1%.

PROPOSED CHANGES TO ISO 18489

The test standard for the CRB test, ISO 18489:2015, is currently under revision. Including more elaborate instructions to determine the initial crack length a_{ini} has been proposed. As the method of measuring A_{ini} is the most appropriate, this method is currently favoured. This means image processing software must be used to determine the initial unnotched surface area (A_{ini}) and corresponding initial ligament diameter (D_{ini}) after testing. This is carried out using at least three points to construct a circle that covers the fracture area. Proposals have also been made to measure both the top and the bottom sides of the fracture surface and use the average of the two measurements to calculate a_{ini}. If the difference in D_{ini} between the two sides exceeds 0.2 mm, both sides must be measured again and the average of four measurements used to calculate a_{ini}. This will limit the error resulting from carrying out a single measurement.

CONCLUSION AND OUTLOOK

This paper shows that there are multiple ways to measure the notch depth in a CRB test specimen. The current test standard, ISO 18489:2015, is insufficiently clear about how to measure the notch depth. This will be corrected in a revision of the test standard, which is currently being developed.

Evaluation of the results of the measurements made by the analysts also shows that those with the most experience produce measurements with less scatter (analysts 1 and 2). A possible source of overestimation may be misidentification of the notch transition point, as what may seem to be the end of the notch is often followed by a subtle continuation. This highlights the importance of clear instructions and proper training to ensure more consistent results and reduced variability.

It is clear that the measurement of the actual notch depth is not as straightforward as it may seem. The consequences are however quite substantial, because a suboptimal measurement may result in a significantly different interpolated failure time, which may in turn lead to a situation in which a material either wrongly meets or fails to meet the requirements. Sufficient attention must be paid to measuring the actual notch depth to limit the error as much as possible.

Identifying the exact onset of the transition remains challenging due to the subjective nature of data interpretation. One promising indicator is the fluid velocity at the trailing edge of the notch and in particular the speed at the very tip of the cut, which may signal the beginning of the transition. To improve accuracy during notching, additional factors should be considered/re-evaluated, including the shape of the knife, the pressure applied during notching and thermal influences.

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