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Inexpensive fracture toughness testing of welded steel

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Abstract. In a prior project, TNO has presented a low-cost way of finding fracture toughness of base materials for cleavage fracture. That method features a small-scale CTOD specimen, combined with simplified sensors, less fatigue pre-cracking, faster testing, and no need for a temperature chamber. This method has been extended to welds by considering the effect of pop-ins. This paper summarizes the prior method and the justifications for it before extending it to welded structures by introducing adjustments for pop-ins for small-scale specimens.

Keywords: Small-scale specimens, cleavage, toughness, high-strength steels.

1 Introduction

As the maritime and offshore industry moves to larger and stronger structures, they need to use thicker and stronger steels than ever before. Increased thickness and strength increase the risk of brittle fracture. The Charpy test is a practical, empirical testing technique that is currently in wide use to help assure safety against fracture, but that technique was developed without our modern understanding of fracture. Its limitations are becoming more important for future structures. Other fracture testing (e.g. CTOD and J-integral) can give more understanding of the material's fracture toughness, but this testing is too expensive to be used in a routine enough fashion to assist material development or standard quality assurance. TNO has addressed this gap by developing a low-cost version of CTOD testing [1], which has five key features:

- A shorter fatigue pre-crack, which reduces test specimen preparation time [2]
- A higher load application rate, which is more representative of loading on real structures [3]
- A fixed specimen size [4]
- Simpler sensors [5]
- No need for a temperature chamber for low-temperature testing [1]

A good correlation was shown between this method and conventional CTOD tests on base materials for CTOD values less than 0.2 mm.

The current paper extends the applicability of the method described above from base material specimens to welded specimens by addressing some specific topics:

- Laboratory independence
- The selection of the representative location within the weld zone for removing the specimen – both in the through-thickness direction and perpendicular to the weld
- The orientation of the crack front relative to the weld
- Accounting for the relative importance of pop-ins for small versus large specimens

The above differences from standard testing are outlined in the subsections below.

2 Background

The Crack Tip Opening Displacement (CTOD, or δ) is a measure of elastic-plastic fracture toughness. The stress intensity factor (K_I) is a way of representing fracture toughness based on linear-elastic theory. It is common practice (e.g. by BS 7910 [6]) to assume that there is a unique relationship between these two parameters, which is:

$$K_I = \sqrt{\frac{m\sigma_y \delta E}{1-\nu^2}} \tag{1}$$

where m is a material constant that can be found based on the hardenability of the material, E is the Young's modulus, v is the Poisson's ratio, and σ_y is the yield stress. Throughout this document, it is assumed that K_I and CTOD can be converted back and forth. I.e. it is assumed that if a CTOD is found by testing that it can be converted into a K_I, operated on, and converted back.

A common way of testing CTOD is by the use of a Single Edge-Notched Bending (SENB) specimen, which is typically taken as a bar that has a notch in it and is pre-fatigued to extend the notch. The fatigue crack is loaded until the specimen breaks by a 3-point bending apparatus. The thickness of the specimen has been traditionally specified as the thickness of the base material, and the other geometric parameters have been traditionally specified as being proportional to that, resulting in very large specimens when thick steels are being considered.

3 Small-size specimen

Testing fracture toughness of materials based on sub-size specimens was demonstrated for base material in the AFSuM-1 program [4]. Using sub-size SENB specimens according to the AFSuM procedure [1] avoids the expensive procedure of testing conventional specimens with dimensions based on the thickness of the plate. The cost of testing specimens with full size dimensions according to BS7448 [7] and similar standards is becoming increasingly important now that thicker materials and high strength steels are becoming more common. Thicker pieces of steel, especially of high strength steels like S690, require increasingly stronger testing equipment and bigger climate chambers in case low temperature testing is required. The fixed size SENB specimen (10x20 mm) that was proposed in AFSuM-1 showed accurate results for CTOD values up to 0.2 mm when adjusted by the Master curve equation [8]:

$$K_{B1} = K_{min} + (K_{B2} - K_{min}) \left(\frac{B_2}{B_1}\right)^{1/4} \quad (2)$$

where B_1 and B_2 are the thicknesses of specimens 1 and 2, respectively, K_{B1} and K_{B2} are the critical stress intensity factors of specimens 1 and 2, respectively, and K_{min} is the minimum toughness for the material, which is typically taken as 20 MPa√m. This equation accounts for the statistical likelihood of encountering a critical brittle particle at the crack tip as a function of the length of the crack tip (typically taken as the thickness of the specimen), and it is enjoying wide acceptance, such as inclusion into BS7910 [6]. The maximum toughness of a CTOD of 0.2 mm was seen as a weakness of AFSuM, so the prescribed, fixed specimen size was increased in the AFSuM-2 project to accommodate a slightly higher maximum CTOD value, which is currently estimated to be 0.25 mm. For that purpose, the specimen size was increased to 15x30 mm.

4 Faster testing

Conventional toughness testing requires that the material is tested in a slow rate, typically specified in terms of stress intensity factor rate. For example, ISO 12135 [9] indicates that the tests should be performed at a rate between 0.2 MPa $m^{0.5}$ s^{-1} and 3 MPa $m^{0.5}$ s^{-1}. There are a number of specific limitations with this approach, which include:

- For a constant loading velocity of an elastic-plastic specimen, the stress intensity rate will change during the course of the test
- This rate is much slower than is found in application [3]
- A CTOD rate may be more suitable when the CTOD is being tested and measured.
- Experiments are typically performed in displacement control, but stress intensity factors are determined entirely on force. Therefore, converting from a stress intensity rate to a crosshead velocity requires foreknowledge of the specimen (and possibly test frame) stiffness.

Therefore, the authors propose within the AFSuM projects that the loading rate should be specified in terms of CTOD rate and specified such that the maximum force is reached within two seconds of initial loading. This loading time is based on loading rates experienced in maritime and offshore application.

4.1 Relating crosshead velocity to CTOD rate

A SENB CTOD specimen is shown in Fig. 1. If the two halves of the specimen rotate around point on the ligament above the crack, then the analogy of similar triangles can be expressed in the equation below:

$$\frac{\delta}{r(W-a)} = \frac{V}{a+r(W-a)} \tag{3}$$

where δ is the CTOD, V is the Crack Mouth Opening Displacement (CMOD), a is the crack length, r is the hinge location as a fraction of the ligament size, and W is the height of the specimen. Solving this equation for δ and assuming that $r = 0.4$ (that is, the center of rotation is 40% of the way from the crack tip to the back face of the ligament) will result in:

$$\delta = \frac{0.4(W-a)}{0.6a+0.4W}V \tag{4}$$

which is the expression given by ISO 12135 [9] for the plastic portion of the CTOD for the SENB specimen. This shows that the analogous triangles approach is accepted in norms, and that the assumption that $r = 0.4$ is accepted. If halves of the specimen are acting rigidly, then the angle that the crack mouth opens is equal to twice the angle moved by a half of the specimen, as indicated in Fig. 1. This gives the following relationships:

$$sin\theta = \frac{\delta/2}{r(W-a)} \tag{5}$$

$$tan\theta = \frac{q}{S/2} \tag{6}$$

where q is the load-line displacement, and θ is given in Fig. 1. Combining these equations to eliminate θ and solving for CTOD (δ) yields:

$$\delta = 2r(W-a)sin\left[tan^{-1}\left(\frac{2q}{S}\right)\right] \tag{7}$$

With the small angle approximation, this expression becomes:

$$\delta \cong \frac{4r(W-a)}{S}q \tag{8}$$

The parameters W and S are geometric parameters and don't change during the experiment. A similar method to derive the relationship between a double clip-gage measurement and the load-line displacement is given in ISO 12135 [9]. The change of r and a during the experiment up to the point of fracture is assumed to be negligible. Therefore, only q depends on time, so that the CTOD rate becomes:

$$\dot{\delta} \cong \frac{4r(W-a)}{S}\dot{q} \tag{9}$$

where the over-dot represents differentiation with respect to time. In a standard proportional specimen in which $a/W = 0.5$ and $S = 4W$, this reduces to:

$$\dot{\delta} \cong \frac{r}{2}\dot{q} \cong 0.2\dot{q} \tag{10}$$

It is interesting to notice that this number is invariant of the size of the specimen so long as it is proportional. Therefore, the same crosshead velocity will always result in the same CTOD rate, regardless of the specimen size.

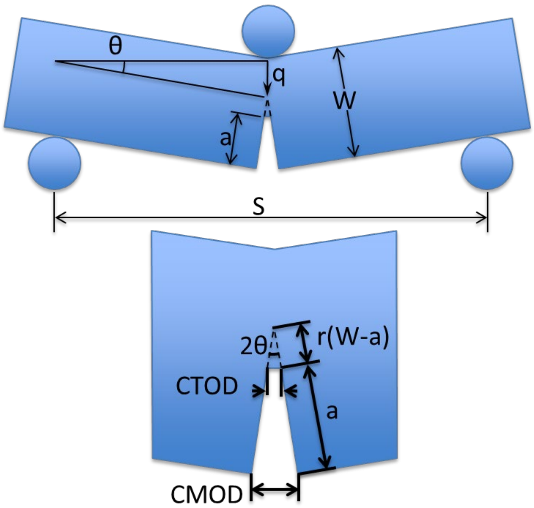

Fig. 1. SENB CTOD specimen illustrating the similar triangles used for relating CMOD to CTOD and load-line velocity to CTOD rate.

4.2 Recommended loading rate

The prior section showed that there is an approximately proportional relationship between the load-line velocity (approximately equal to the crosshead velocity) and the CTOD rate. It was shown in section 3 that the maximum testable CTOD is approximately 0.25 mm. The authors recommend that the testing velocity should be 2-2.5 mm/s, which would result in a CTOD rate of approximately 0.4-0.5 mm/s. Assuming a maximum CTOD of 0.25 mm, this would result in a test duration of approximately 0.5-0.625 s, which is slightly faster than would be expected for a real structure to be loaded. This crosshead velocity is also easily attainable for many hydraulic testing frames.

The authors believe that by specifying a velocity (or, equivalently, a CTOD rate), it will be easier to relate the loading rate of the experiment to that of the real structure and choose a crosshead velocity than is done in traditional fracture testing.

5 Shorter fatigue pre-crack

By its very nature, fatigue crack propagation requires thousands of cycles. This can be accelerated by using a higher loading frequency, but it will invariably require machine and technician time. ISO 12135 [9] requires that the specimen be fatigue pre-cracked to 1.3 mm or 2.5% of the specimen height, whichever is greater. In the case of a specimen that is 15 mm thick by 30 mm high (as indicated in this procedure), the 1.3 mm fatigue pre-crack extension is larger. It was shown in [2] that the enclosing angle from the crack tip to the notch (indicated as β in Fig. 2) is more important than the absolute length of the fatigue crack. This was found by creating FEA models of several different specimens which all had a thickness of 10 mm and a height of 20 mm. In all of the specimen models, the fatigue pre-crack ended at the same place, but they made up different proportions of the combined notch and fatigue pre-crack length. In the most extreme case, only a crack was present (thus, no notch), representing a fatigue pre-crack of 10 mm. In other cases, the notch was most of the length, and the fatigue pre-crack was very short. Fig. 3 shows that for different notch tip geometries, the general pattern followed a rule that the β angle dominated the behavior. From this study, it was recommended that the β angle should be less than 40° in order to achieve within 1% of the results that have no influence of notch. Based on the advice of a machine shop, it is believed that a notch tip angle (θ) of 90° and a notch width (H_n) of 0.5 mm was machinable with traditional methods. Based on these dimensions, a fatigue pre-crack length of 0.5 mm would result in an angle just under 40°, which is a 60% reduction in the required fatigue pre-crack length relative to standards.

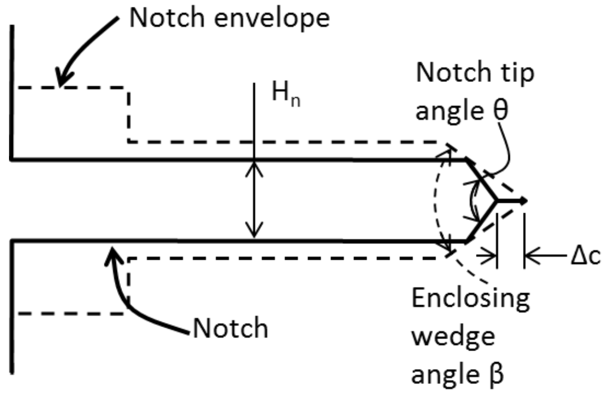

Fig. 2. Definition of a notch and a fatigue pre-crack extension, along with the bounding notch, from [2]

6 Simpler sensors

Standard fracture toughness testing typically requires a local displacement sensor. For example, CTOD testing typically requires a clip gage, or a CMOD sensor. Likewise, *J*-integral testing typically requires a local load-line displacement sensor. For example, see ISO 12135 [9] for details. It is often believed that this is necessary in order to account for the effect of testing frame compliance on the results. However, unlike tension testing, fracture testing typically separates the linear elastic portion from the plastic portion. The linear elastic portion of the *J*-integral or CTOD test is typically represented by a conversion from stress intensity factor, which only depends on force. The plastic portion of both calculations depends only on the plastic portion of the displacement, whether it is the load-line displacement (in the case of *J*-integral) or the CMOD (in the case of CTOD). Because only the plastic portion is considered, the linear elastic portion is typically removed from the sensor record. That means that any linear elastic compliance that is imposed on the displacement record (for whatever reason) doesn't affect the results at all. This was tested in [5], and many experiments were considered with different levels of toughness. For each experiment, the toughness was measured by the CTOD through the traditional CMOD method and then compared to the CTOD as determined from the *J*-integral, as found from the crosshead displacement. That study showed that the differences between these two methods was attributable to noise on the different signals, rather than to the potential of having frame compliance represented in the signal. Based on these findings, the authors recommend that the CMOD sensor (a.k.a. clip gage) can be used if desired, but a properly-calibrated and linear elastic crosshead displacement should be adequate.

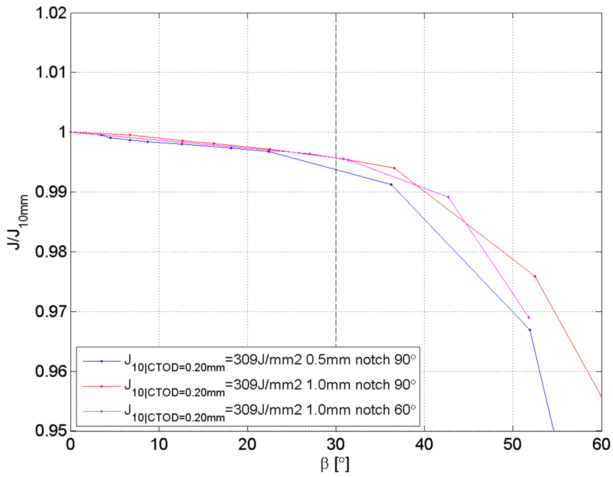

Fig. 3. Effect of the bounding notch angle *β* on the calculated *J*-integral, as a fraction of the *J*-integral that would result from a crack that is 10 mm with no notch. From [2].

7 No climate chamber

In section 4, it was suggested that a faster loading rate should be used, resulting in a test that doesn't last longer than 2 seconds. With the recommended loading rate and maximum testable CTOD value, the test is expected to last about half of a second. Based on this realization, it is believed that specimens will not warm appreciably during the loading process. In prior studies [1], a heat transfer analysis has been performed on the test setup. It was found that the dominant heating mode is from contact with the rollers. Convection on the free surfaces was considered, but appeared to only result in a temperature difference from the surface to the core of less than one degree Centigrade. The analysis of heat introduction through the rollers revealed that isothermal surfaces were essentially cylinders with their central axis being the three points of contacts with the three rollers. In this way, it was shown that the thermocouples needed to be located very close to the tip of the fatigue pre-crack, but it was otherwise representative of the state of the material in the center.

Based on the above observations, an alternative cooling process was chosen whereby no climate chamber is needed. This saves the need for a climate chamber, and it also eliminates the need of bringing specimens into thermal equilibrium before testing. The new cooling method consists of the following steps:

- The specimen is fitted with a thermocouple. Laboratory independence testing has revealed that the proximity of this thermocouple to the crack tip is very important, so recommend applying a thin-gaged thermocouple very close to the crack tip is recommended.

- The specimen is immersed into liquid nitrogen and allowed to approach equilibrium.
- Once the specimen is cold enough (typically, when the thermocouple reads -196°C), the specimen is placed on holders within the test frame. These holders position the specimen in the test frame but don't allow for it to touch metal.
- The specimen warms up to 20°C below the desired test temperature based on convection with the laboratory air.
- When the specimen is warmed up to 20°C below the desired test temperature, the specimen is compressed between the three rollers of the three-point bending fixture. The testing machine automatically switches into force control and holds contact with a low, constant force.
- The specimen warms at a faster rate now that it is in contact with the rollers. When the thermocouple reads 1-2°C below the stated test temperature, the final loading is started.
- The crosshead advances at 2-2.5 mm/s until the specimen breaks.

While this cooling and loading method may appear complex, it becomes more natural after the first or second repetition of the method and can be done quickly and efficiently after a little bit of practice. The ultimate result is that the specimens can be tested at sub-ambient temperatures without the use of a climate chamber. While this method has been demonstrated in two laboratories, it may need to be correlated positively in other laboratories before wider application.

This cooling is not the same as the cooling method recommended for Charpy testing, but it does bear some similarities. With both situations, the specimen is assumed to have an approximately constant temperature while a short-duration test is performed and the specimen is out of thermal equilibrium.

8 Scaling of pop-ins

Pop-ins are a physical phenomenon in which unstable fracture is initiated and then self-arrests during testing. This results in a sudden drop in force and/or increase in displacement, as shown in a rather extreme case in Fig. 4. The occurrence can affect the measured fracture toughness of the material under certain conditions. In the extension of the AFSuM method to welded materials, this effect becomes important, since one of the main causes of pop-ins are local brittle zones (LBZ) due to the welding process. Other causes for pop-ins are splits, ice fracture and noise in the data signal. The standards NEN-EN ISO 15653 [10] and BS7448-1 [7] describe an identical procedure to follow once a pop-in is detected after testing. Pop-ins where a force decrease or displacement increase up to 1% is found are to be ignored. Bigger pop-ins are considered significant (and therefore will affect the measured fracture toughness), unless they are shown to be insignificant by fractographic and metallographic procedures [7, 10]. Pop-ins caused by local brittle zones are directly related to the microstructure that is sampled at the crack-tip of the SENB specimen. Due to their smaller size, sub-sized specimens will suffer more from a local brittle zone than full size specimens, given that the physical size of the LBZ is constant. A method to account for that is presented in [11], where a pop-in acceptability requirement is presented based on the criterion set in ISO 15653 [10]. This method uses an analytical derivation of the stress field ahead of the crack-tip, known as the Prandtl field, and the assumption that a pop-in occurs instantaneously to find a formula to relate pop-in severity in terms of force drop to the size of a local brittle zone. Then, using SEM pictures to find the size of an actual LBZ in a specimen and converting that with the newly introduced formula to a force drop, a result similar to the force drop observed in the test itself was found. Using this formula, a relationship was derived to relate the maximum allowable force drop (1%) in full size specimens to a bigger drop in sub-size specimens. The relationship that was found is shown graphically in Fig. 5. This figure shows what the maximum allowable force drop would be for a 15 by 30 mm specimen if it is assumed that a 1% force drop on a full-thickness specimen is assumed to be acceptable.

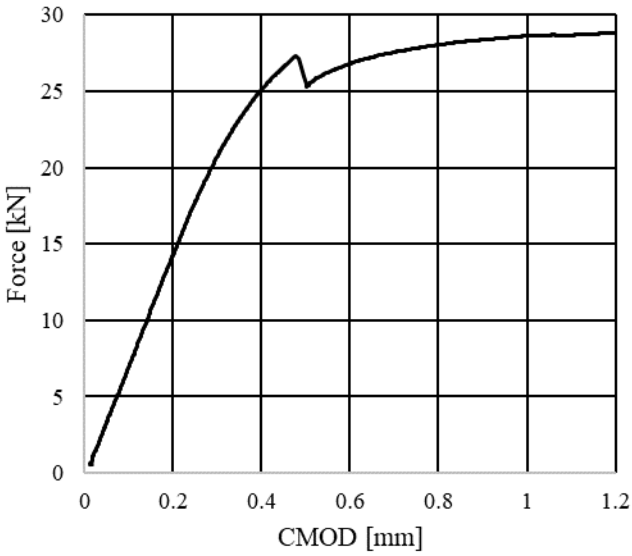

Fig. 4. Example of a force-CMOD curve exhibiting a pop-in. From [11].

On the horizontal axis the original plate thickness is indicated and the vertical axis shows the allowable pop-in in a 15x30 mm specimen taken from that plate. In other words, the allowable pop-in in the sub-size specimen is equivalent to a pop-in of 1% in a full size specimen from a plate of thickness B.

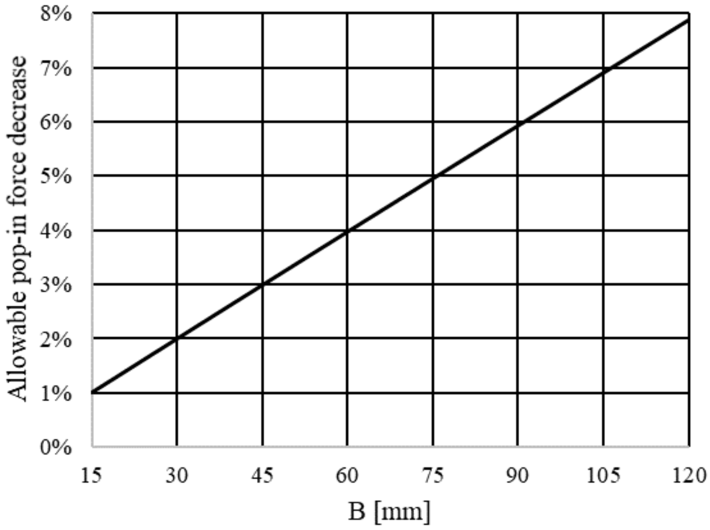

Fig. 5. Allowable pop-in size for a 15x30 mm specimen assuming the identical, acceptable pop-in for a thicker specimen. From [11]

9 Conclusions

This paper describes several modifications to standard CTOD testing. Some of the modifications are aimed at reducing the cost of CTOD testing such that it can be performed more regularly, for example:

- Smaller specimens
- Faster testing
- Simpler sensors
- No temperature chamber

A post-processing modification was designed to ameliorate a disadvantage of small-scale testing with respect to large-scale testing:

- Adjust for pop-in size

Finally, one of the changes is aimed at bringing the testing into closer resemblance with application, specifically, testing at a loading rate that is similar to real structures (thus, much faster than traditional quasi-static fracture toughness testing). Taken together, this combinations of modifications to standard CTOD testing allow for a lower-cost fracture toughness testing method that is nevertheless a reasonable estimate of the value that would be found from standard testing.

10 Acknowledgements

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