The methods for determining the CTOD at crack initiation

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The crack tip opening displacement (CTOD), just like J integral, is a parameter characterising the fracture toughness of materials. The CTOD values are typically determined at subcritical crack initiation, \( \delta_{i_c} \), or at 0.2 mm subcritical crack extension, \( \delta_{SZW} \). The procedure for measuring \( \delta_{i_c} \) is described in detail in ASTM 1820. Measuring \( \delta_{SZW} \) is far more complicated and requires specialised apparatus and trained operators. The aim of this study was to assess the capability of different methods used for determining the value of \( \delta_{i_c} \). The results from the experiments were compared with those from numerical calculations, obtaining good agreement between \( \delta_{i_c} \) data determined by the methods applied. The CTOD was measured on SENB (single-edge-notch-bend) specimens made of S355JR steel subjected to laboratory based heat treatment. The tests were performed at temperature in the range –80°C to 20°C, which allowed assessing the impact of reduced temperature on the \( \delta_{i_c} \) level.

Key words: crack tip opening displacement, fracture toughness, S355JR steel.

1. INTRODUCTION

The process of subcritical crack growth under a monotonically increasing load in an elastic-plastic material comprises three stages — crack tip blunting, subcritical crack initiation and crack propagation [1]. Determination the moment of initial subcritical crack in components (or specimens) under loading is problematic. A lot of attention has been devoted to predicting the critical value of fracture toughness in elastic-plastic materials in fracture mechanics tasks. A some of methods have been developed and standardized in relevant specifications, with the most popular being based on the critical value of J-integral — \( J_{i_c} \) or on the critical value of crack tip opening, \( \delta_{i_c} \) [2]. These quantities define the fracture toughness of a material at a chosen point when the average value of subcritical crack growth is 0.2 mm.

The fracture toughness at subcritical crack initiation can be determined by measuring the geometry of the blunted crack tip, as proposed by Shih [3] (Fig. 1). The blunting of a primary sharp crack tip proceeds until subcritical crack initiation, and the radius of the blunted crack is dependent on the strength and plastic properties of the material. The assumptions of Shih’s model can be used for calculation of the crack tip opening displacement at crack initiation by measuring the stretch zone width (SZW), \( \Delta a_{SZW} \): 

\[
d_{n} = 2 \cdot \Delta a_{SZW} 
\]

The blunting crack tip at moment according to start subcrack are shown in Figure 1. The view presented the situation in a axis plane that the fracture surfaces should be examined in the scanning electron microscope (SEM).

This paper reports the results of the study carried out to determine the crack tip opening displacement at subcritical crack initiation, \( \delta_{i_c} \). Test temperature ranged from –80°C to 20°C to cover different properties of the test material. The using various experimental methods and FEM (finite element method) calculation let possibility compared the results.

The value of CTOD at the start of subcritical crack, \( \delta_{Ti} \), (and according value of J-integral, \( J_i \)) can be determined by the stretch zone width (\( \Delta a_{SZW} \)). This method was first proposed by Japanese researchers and then standardised [5]. European guidelines for the same method are set forth in ISO–12135:2016 [6] and ESIS (European Structural Integrity Society) and GKSS (GKSS-Forschungszentrum, Geesthacht) recommendations [7, 8], with a requirement that the fracture surfaces should be examined in the scanning electron microscope (SEM).

Key words: crack tip opening displacement, fracture toughness, S355JR steel.

Fig. 1. View of blunted crack tip at moment of subcrack start; SEM
2. MATERIAL AND METHODS

The test material was a S355JR (former 18G2A) steel widely used for weldable structural applications, such as tanks and pressure pipes [9]. Laboratory heat treatment were performed for uniform microstructure in tested specimen: heat and annealing at 950°C for 20 minutes and cooled in air and next annealing at 600°C for 150 hours and cooled in oil. This heat treatment regime provided the cylindrical specimens (\(d_0 = 5\) mm, \(L_0 = 25\) mm) [13]. The relationships of the true stress, \(\sigma_t = \sigma_t(1 + \varepsilon_n)\), as a function of logarithmic strains, \(\varepsilon_n = \ln(1 + \varepsilon_n)\), were determined (Fig. 3). These relationships are required for material definition during modelling and numerical calculations. The strength characteristics determined from \(\sigma_t\)–\(\varepsilon_n\) relations are given in Table 1.

In order to determine the strength characteristics of S355JR of FC steel, the uniaxial tensile tests were performed on standard cylindrical specimens (\(d_0 = 5\) mm, \(L_0 = 25\) mm) [13]. The relationships of the true stress, \(\sigma_t = \sigma_t(1 + \varepsilon_n)\), as a function of logarithmic strains, \(\varepsilon_n = \ln(1 + \varepsilon_n)\), were determined (Fig. 3). These relationships are required for material definition during modelling and numerical calculations. The strength characteristics determined from \(\sigma_t\)–\(\varepsilon_n\) relations are given in Table 1.

The crack tip opening displacement was measured on single notched bend specimens, SENB, \((W = 24\) mm, \(S = 96\) mm, \(B = 12\) mm, \(a_0/W = 0.55\)). Signals of force \(F\), crack opening at the specimen edge \(\delta_{OP}\) and deflection at the loading point \(u_F\) were recorded during the loading process at current time. Based on the recorded signals, the critical values of the crack tip opening \(\delta_{IC}\) and \(J\) integral — \(J_{IC}\), were calculated according to ASTM E1820 procedures [2]. The values of crack tip opening displacement at subcritical crack initiation, \(\delta_{IC}\), were determined from the SENB fracture surfaces using the JOEL scanning electron microscope and the HIROX profilometer. During the FEM loading simulation and \(\delta_{IC}\) calculation the magnitude of the specimen deflection, \(u_F\), corresponded to the value of the integral \(J_i\).

3. NUMERICAL CALCULATIONS

The finite element program ABAQUS (version 6.12) [14] was used to simulate the loading process of tested SENB specimens. Because of the symmetry of the problem, the numerical model assumed a quarter SENB model (Fig. 4a). The crack opening tip was modelled as an arc of 0.012 mm radius. The specimen was divided into 12 layers in the through-thickness direction. In calculations, 8-node three-dimensional finite elements were used. The density of the finite elements was increased with decreasing distance to the crack tip.

An important aspect of numerical simulations is the proper definition of the material model introduced into the program. True tensile curves need to be properly developed based on experimental data from tensile test. The elastic part of the material is defined by two quantities: Young’s modulus, \(E\), and Poisson’s ratio, \(\nu\). The part with plastic hardening is described by pairs of true strain–stress points in range from the yield stress point to the ultimate strength point. For highly plastic materials, such as S355JR steel, the description of the material beyond the strain corresponding to the ultimate strength on the tensile curve is problematic. In this calculation, the true stress–strain curve was interpolated to 3 mm/mm of strain, using a linear approximation of the last 150–200 points from the curve.

In numerical calculations, displacement applied on the upper roller corresponded in value to the moment of subcritical crack initiation. The CTOD was measured on SENB specimens at the points shown schematically in Figure 4b. The measurements were made with a step of 0.5 mm, from the specimen axis plane (layer 0) to a distance of 6 mm (to the side face of the modelled SENB specimen). The FEM calculated CTOD values are given in Table 2. The data shows that almost the same level of CTOD is maintained in the centre of the specimen up to ~2.5 mm from its plane of symmetry. A gradual decrease of the CTOD values was observed with decreasing distance to the side face of the specimen.

![Fig. 2. Ferrite microstructure of S355JR steel with coagulated carbides; SEM](Image)

Rys. 2. Mikrostruktura ferrytyczna stali S355JR ze skoagulowanymi cząstkami węglików; SEM

Table 1. Mechanical properties of S355JR FC steel at various temperature

<table>
<thead>
<tr>
<th>Mechanical properties</th>
<th>Test temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+20°C</td>
</tr>
<tr>
<td>(E), GPa</td>
<td>211</td>
</tr>
<tr>
<td>(\sigma_{UTS}), MPa</td>
<td>380.26</td>
</tr>
<tr>
<td>(\sigma_{UTS}), MPa</td>
<td>392.73</td>
</tr>
<tr>
<td>(\sigma_{YS}), MPa</td>
<td>588.45</td>
</tr>
<tr>
<td>(n)</td>
<td>4.92</td>
</tr>
<tr>
<td>(\nu)</td>
<td>0.3</td>
</tr>
</tbody>
</table>

![Fig. 3. The graphs of true \(\sigma_t\)–\(\varepsilon_n\) relations of S355JR FC steel at test temperature](Image)

Rys. 3. Wykresy rzeczywiste \(\sigma_t\)–\(\varepsilon_n\) stali S355JR w różnej temperaturze badania
4. MEASUREMENTS OF THE STRETCH ZONE WIDTH

To determine the critical values of fracture toughness characteristics at the moment of subcritical crack initiation, CTOD — $\delta_T$, and $J$ integral — $J_{IC}$, the measurement of the stretch zone width $\Delta a_{SZW}$ should be performed. The measurement was made on fracture surface of tested SENB specimen used to determine the critical values of fracture toughness, $\delta_T$, and $J_{IC}$ in accordance with ASTM E1820 [2].

The SZW measurement area on the fracture surfaces was chosen to be near the axis plane so that it was in the region of plane strain state. The measurement was performed to the ESIS [7] and GKSS [8] guidelines and ISO–12135: 2002 [6] using the JEOL JSM 7100F scanning electron microscope and the HIROX-400 optical profilometer. The SEM measurement comprised two phases. In the first phase, SZW photographs were made and next they to be subjected the area calculation using the ImageJ image processing program [15]. The software allowed estimating the stretch zone surface area and obtaining the average value of the stretch zone width [16] (Fig. 5). The stretch zone photographs were taken at five points along of 1.5 mm from the fracture surface axis. The distances between the central points of the areas being photographed were kept constant at 300 μm. This was possible owing to the ability to control the position of the table in the Jeol 7100F scanning electron microscope chamber.

The second method used in this study for evaluating the stretch zone width based a linear of fracture surface area profile obtained by the Hirox optical profilometer. Surface profiles were obtained with a magnification of 400x. The measuring area was selected identical as in the SEM method, with the length of 1.5 mm from axis plane. Within this length, 11 profiles of linear surfaces were made with a constant distance of 150 μm. The position of the example linear profiles on the fracture surface is shown in Figure 6a. The SZW was determined from the profile lines (Fig. 6b) and the image of the surface fracture.

![Fig. 5. View of stretch zone on specimen fracture surface; SEM](image)

![Fig. 6. Fracture surface determined with profilometer (a) and fracture linear profile (b)](image)
The SZW measurement results for tested specimens based on SEM and Hirox equipment are presented in Table 3.

In the Figure 7 as example are shown the results of δ_{T} obtained by SEM, Hirox measurements and FEM calculation in interval from axis plane to 1500 μm. The FEM calculated δ_{T} values within this section of the specimen have almost constant levels. The results based on Hirox profilometer characteristics highest random of data. Average δ_{T} value received by Hirox measurement and by FEM calculation are similar. Some lower δ_{T} values obtained based on SEM photographs. These differences can explained some difficulties in fixing of accurate SZW dimensions. The scattered values of δ_{T} observed in the methods based on SZW measurements result from the non-uniformity of the fracture surface microrelief due to the heterogeneity of microstructure morphology, composed of layers of ferrite grains and ferrite grains with particles of coagulated pearlite, and the difficulty determining the boundaries of the stretch zone.

Unfortunately, these methods depend on the accuracy and experience of the operator performing the measurements. The results obtained by FEM calculation are nearly stable data to the assumed material model. For all methods the δ_{T} values decrease with increase distance from axis plane of specimen. With the lowering of the test temperature the δ_{T} values decrease regardless of the method used.

### Table 3. The δ_{T} values determined by SEM and Hirox methods measurements

#### Table 3. Wyniki pomiarów δ_{T} wykonanych za pomocą mikroskopu (SEM) oraz profilometru (Hirox)

<table>
<thead>
<tr>
<th>T °C</th>
<th>Measurement method’s</th>
<th>Distance from the axis plane, μm</th>
<th>δ_{T} Values, μm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>300</td>
</tr>
<tr>
<td>+20°C</td>
<td>SEM</td>
<td></td>
<td>285.58</td>
</tr>
<tr>
<td></td>
<td>HIROX</td>
<td></td>
<td>257.78</td>
</tr>
<tr>
<td>-50°C</td>
<td>SEM</td>
<td></td>
<td>72.84</td>
</tr>
<tr>
<td></td>
<td>HIROX</td>
<td></td>
<td>121.32</td>
</tr>
<tr>
<td>-80°C</td>
<td>SEM</td>
<td></td>
<td>25.06</td>
</tr>
<tr>
<td></td>
<td>HIROX</td>
<td></td>
<td>28.43</td>
</tr>
</tbody>
</table>

### Table 4. The average critical values of δ_{TC} obtained according to the different test methods

#### Table 4. Średnie wartości RWP δ_{TC} uzyskane przy wyznaczaniu różnymi metodami badawczymi

<table>
<thead>
<tr>
<th>T °C</th>
<th>δ_{TC}, μm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>20°C</td>
<td>22.0</td>
</tr>
<tr>
<td>-50°C</td>
<td>73.96</td>
</tr>
<tr>
<td>-80°C</td>
<td>22.02</td>
</tr>
</tbody>
</table>

### 5. SUMMARY

The fracture process in component of elastic-plastic material is complicated. In each of component before of crack tip at the same time are presented different stress states: plane strain, central plane stress, in side; and mixed state. Participation of each state depends of material properties and size of components. Because the results of CTOD received of measurements in central part of specimens will be higher than ones from further regions. A difference between level of δ_{T} depends of plasticity of material. The difference of δ_{T} values measured in central part and near side plane of specimen decrease with decreasing plasticity, and respectively decrease with temperature lowering [17].

The average critical values of CTOD obtained at different methods using are listed in Table 4. You can sawn some random of presented results. These differences are consequences of various procedures using for assessed critical values of CTOD. Reasons about objective and subjective courses that impacts on δ_{T} values results during its assess by SEM and Hirox profilometer equipment’s are given in previous chapter. Nonetheless the methods based on testing SZW allows obtained the δ_{T} values in concrete places along crack front. First subcrack initiate in the central part before of pre-crack of specimen, and respectively the δ_{T} values are highest among other received values along a crack front. Result of δ_{T} directly according to Shih model (Fig. 1) obtained as single in axis plane. In next parallel plane the value of could be little different.

The ASTM E1820 procedure gives possible estimated CTOD value at 0.2 mm subcritical crack extension, δ_{TC}. According to the ASTM E1820 procedure δ_{TC} are determined basing on data of crack mouth displacement (Δu_{CM}), which represented some average value along specimen thickness. Therefore δ_{TC} value for high plastic material would be lower than data δ_{T} obtained of measurement made in central part of specimen. The temperature decrease lead to material plasticity decreasing, when δ_{TC} value could be some higher than δ_{T}.

The using FEM method and numerical simulation for δ_{T} evaluate seems most promising. Due unified material using in model we eliminate data random occurring in SEM and Hirox profilometer measurement. The FEM allows obtain δ_{T} in each points along a crack profile. However, the drawbacks of FEM methods of δ_{T} calculation are some simplifications in modelling. First simplification — is modelling of crack front as straight line, when one has arc-shape profile. Second simplification concerns taking into account influence of parameters Lode and three-dimensional stress state on material modelling [18–20]. Consideration of this factors would allowed increased accuracy of obtained results.

### ACKNOWLEDGEMENTS

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Fig. 7. The data of δ_{T} values calculated by MES and measured by SEM, HIROX methods along front of the crack for testing temperature +20°C

**Rys. 7. Wartości δ_{T} wyznaczone za pomocą MES, mierzone na mikroskopie (SEM) oraz profilometrze (Hirox) wzdłuż frontu pęknienia, temperatura +20°C**
REFERENCES

Metody wyznaczania rozwarcia wierzchołka CTOD podczas inicjacji pęknięcia

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Słowa kluczowe: rozwarcie wierzchołka pęknięcia, charakterystyki odporności na pękanie, stal S355JR.

1. CEL BADAŃ

Rozwarcie wierzchołka pęknięcia, podobnie jak całka \( J \), charakteryzuje odporność materiału na pękanie. Wartości rozwarcia pęknięcia wyznacza się podczas inicjacji pęknięcia podkrytycznego, \( \delta_{\text{TC}} \), lub po osiągnięciu przez pęknięcie podkrytyczne przyrostu 0.2 mm, \( \delta_{\text{Ti}} \). Procedura wyznaczania \( \delta_{\text{TC}} \) jest szczegółowo opisana w normie ASTM 1820. Wyznaczanie wartości \( \delta_{\text{Ti}} \) jest bardziej skomplikowane, wymaga specjalistycznego sprzętu i wykwalifikowanego personelu. W artykule przedstawiono kilka metod wyznaczania \( \delta_{\text{Ti}} \).

2. MATERIAŁ I METODYKA BADAŃ

Material do badań stanowiła stal gatunku S355JR (18G2A) poddana laboratoryjnej obróbce cieplnej: normalizowaniu (wygrzewanie w temperaturze 950°C przez 20 minut i chłodzenie na powietrzu), oraz w drugim etapie obróbki wygrzewaniu w temperaturze 600°C przez 150 godzin i chłodzeniu w oleju. W wyniku zastosowanej obróbki cieplnej uzyskano w stali S355JR mikrostrukturę ferrytu ze skoagulowanymi cząstkami węglików (FC). Podobny typ mikrostruktury można zaobserwować w strefie wpływu ciepła w spawanych elementach ze stali S355JR oraz w elementach po długotrwałej eksploatacji w podwyższonej temperaturze. W celu wyznaczenia charakterystyk wytrzymałościowych stali S355JR z mikrostrukturą typu FC przeprowadzono jednoosiową próbę rozciągania na standarycznych cylindrycznych próbkach. Rozwarcie wierzchołka pęknięcia (RWP) wyznaczono, wykonując badania próbek trójpunktowo zginanych, SENB, o wymiarach: \( W = 24 \text{ mm}, S = 96 \text{ mm}, \ B = 12 \text{ mm}, a_{0}/W = 0.55 \). Wartości rozwarcia wierzchołka w momencie inicjacji pęknięcia podkrytycznego zostały wyznaczone na podstawie badań przelomów próbek SENB wykonanych za pomocą skaningowego mikroskopu elektronowego JOEL oraz profilometru HIROX. Wykonano ponadto symulacje obciążenia metodą elementów skośnych (MES), zadając wielkość ugięcia próbki \( u_{\text{F}} \), która odpowiadała wartości całki \( J \).

3. WYNIKI I ICH DISKUSJA

Średnie wartości rozwarcia wierzchołka pęknięcia \( \delta_{\text{Ti}} \) dla odcinka pomiarowego 1500 μm uzyskane z zastosowaniem różnych metod badawczych zamieszczono w tabeli 3. Zbliżone poziomy wartości RWP w momencie inicjacji pęknięcia podkrytycznego otrzymano w wyniku obliczeń numerycznych oraz za pomocą pomiarów na profilometrze HIROX, nieco mniejsze wartości RWP — za pomocą pomiarów szerokości strefy stępienia.

4. PODSUMOWANIE

W artykule przedstawiono wyniki badań przeprowadzonych w celu wyznaczenia wartości rozwarcia wierzchołka pęknięcia początkowej w chwili inicjacji pęknięcia podkrytycznego \( \delta_{\text{Ti}} \). Wyniki uzyskane według różnych metod badawczych wskazują, że wartość RWP zmienia się wzdłuż frontu szczeliny. Maksymalne wartości występują w środkowej części próbki, gdzie występuje dominacja płaskiego stanu odkształcenia. Wraz ze zbliżaniem się do bocznej powierzchni próbki wartości RWP stopniowo zmniejszają się.

Podczas wyznaczania wartości \( \delta_{\text{Ti}} \) za pomocą metod pomiarowych obserwowano rozrzuty danych. Jest to spowodowane niejednorodnością mikrostruktury badanej stali, składającej się z pasmowo ułożonych ziaren ferrytu i ziaren ferrytu z cząstkami skoagulowanego perlitu.

Średnie wartości \( \delta_{\text{Ti}} \) wyznaczone na pomiarowym odcinku 1500 μm od płaszczyzny symetrii przelomu zmniejszają się wraz ze spadkiem temperatury badań. Jest to tendencja właściwa dla charakterystyk odporności na pękanie w zakresie przejścia kruchoplastycznego.