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RECOMMANDATIONS POUR LES ESSAIS DE TENACITE EN J ET CTOD SUR LES JOINTS SOUDES EN SITUATION DE MISMATCH. POINT DE VUE DE GKSS ET EDF

RECOMMENDATIONS FOR J AND CTOD TESTING OF STRENGTH MISMATCHED : GKSS AND EDF VIEW
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SYNTHESE :

Ce document propose des recommandations pour évaluer la ténacité des soudures. Pour l’aspect expérimental, deux méthodes sont proposées : les micro-éprouvettes de traction et la technique du δ₅. Les micro-éprouvettes de traction sont très utiles pour déterminer les propriétés de traction de la Zone Affectée Thermiquement (ZAT) des soudures multipasses et des régions étroites comme les soudures au laser ou par faisceau d’électrons. Le clip δ₅ permet, quant à lui, une mesure directe de l’ouverture en pointe de défaut (CTOD). Il peut être utilisé sur n’importe quel type d’éprouvette ou de structure. Ces deux méthodes expérimentales sont des outils efficaces pour la détermination des propriétés de traction et de ténacité des matériaux métalliques soudés par fusion en incluant les soudages à haute énergie.

Concernant l’évaluation de la ténacité, les procédures d’estimation de J qui prennent en compte les différences de propriétés mécaniques entre le métal de base et le métal déposé sont revues. Une nouvelle procédure couvrant à la fois les défauts en milieu de soudure et les défauts en ZAT est proposée.

Finalement, certaines recommandations sont faites pour des développements futurs.
EXECUTIVE SUMMARY:

Recommendations for toughness testing and evaluation procedures for weldments are given in this paper. For testing aspects, two testing methods are outlined, microflat tensile tests and the δ₅ testing technique. The micro-flat tensile tests are extremely useful to measure tensile properties for the Heat Affected Zone (HAZ) of multipass welds and very thin weld regions such as laser beam or electron beam and is rather universal. It can be applied to any type of test pieces as well as to structural components with surface breaking cracks. These two test methods can provide efficient tools for tensile and fracture testing of metallic materials joined by fusion welding technology including high power beam welding processes.

For toughness evaluation aspects, the J estimation procedures for mismatched specimens are reviewed, including a summary of a new proposal for best estimates of the mismatch on the J integral. The new procedure covers not only weld metal cracks but also HAZ cracks.

Finally some recommendations are given for further development.
1. Introduction

Welded joints are heterogeneous in their mechanical properties as well as in their microstructure. A proper fracture toughness testing procedure of weldments consequently should incorporate such highly heterogeneous mechanical/microstructural features. Existing testing standards (e.g., see [1-4]), however, were established based on homogeneous mechanical/microstructural properties, and thus need appropriate modifications [4-6].

For accurate and meaningful $J$ and $CTOD$ toughness estimates, testing procedures for weldments should consider both aspects of heterogeneous microstructures.
and mechanical properties of the weldments [7-12].

This paper provides recommendations on toughness testing and evaluation procedures for weldments, most of which result from experience gained at both GKSS and EDF for the past ten years. Some testing methods suitable for weldments developed or adopted at GKSS are explained, such as micro-flat tensile tests and δₜ-testing techniques. The $J$ estimation procedures for mismatched specimens are reviewed, including a summary of a new proposal for best estimates of the mismatch effect on the $J$ integral. The new procedure covers not only weld metal cracks but also HAZ cracks. Finally, some recommendations are given for further developments.

2. Determination of Tensile Properties and Degree of Mismatch of Weldments

A weld joint comprises the weld metal (WM), heat affected zone (HAZ) and the base metal (BM) parts each having different properties. The microstructure and mechanical properties of the WM as well as HAZ are affected by the welding process and procedure. Determination of the tensile properties (degree of mismatch) and fracture toughness values of respective part of the welds presents particular problems, due to the heterogeneous nature of the joints and the small width of the HAZ as well as its microstructural complexity. Therefore, the use of existing standard procedures for the mechanical testing of metallic materials requires some modifications on specimen preparation, testing and interpretation of the data for structural weldments.

2.1 All Weld Metal Properties

A complete picture of the strength level and its variation within the weld volume of the multi-pass structural weld metal can be determined by using "all-weld-metal" round tensile specimens removed completely from the weld metal (parallel to the weld direction), as shown in Fig. 1. Determination of the local variations in mechanical properties within the multi-pass weld deposit may require multiple specimens from various locations of the weld metal. For instance, the root passes of many structural welds may exhibit the higher strength than the top side. The average values of yield and tensile strengths should then be used as the tensile properties of the weld metal, $R_{p0.2}^W$ and $R_m^W$, respectively.

2.2 Transverse Tensile Properties of the Weld Joint

Existing testing recommendations for weldments [5,6] allow round tensile specimens oriented transverse to the weld (Fig. 1) as long as they are tapered appropriately
to ensure that all plastic deformation occurs in the weld metal. Testing of flat transverse specimens will provide information on the tensile properties of whole joint. However, there still remains the problem to verify (quantitatively) the soundness of the weld deposit with such specimens. For instance, the strength mismatch would result in a failure in the lower strength base metal (overmatching case), even though the weld metal might contain defects. Although a fracture in the base metal can be considered acceptable, a true evaluation of the tensile properties of the weld metals is not possible under such circumstances.

2.3 Micro-Flat Tensile Specimens for Weld and HAZ Regions

For HAZ of thick multipass weldments or thin section welds such as laser and EB welds, it is not possible to extract standard sized round tensile specimens, simply due to the small size of the target area. The micro-flat tensile specimens (0.5mm thick and 2mm wide) then can be a powerful option for such cases. Figure 2 shows schematically how to extract and to load the micro-flat tensile specimens. The testing of micro-flat tensile specimens provides full stress-strain curves of various locations across the weld joint and hence variations of mismatch ratio $M$ [13,14]. This experimental technique is particularly useful to obtain local mechanical properties for input parameters for numerical analyses of structural weldments and diffusion bonded interfaces [13].

After establishing the mechanical properties of weldments in a unified fashion, one can conduct toughness testing if required.

3. Fracture Toughness Testing of Weldments

The purpose of fracture toughness tests on weldments can generally be divided into two groups:

- Material selection and qualification of weld procedure (including post-weld heat treatment (PWHT), and
- Defect assessment (fitness-for-service evaluation).

The aim of the first group is to obtain lower bound (conservative) toughness values. Due to the highly heterogeneous microstructure in weldments, it is desirable to locate the fatigue crack tip in the most brittle region. The safest approach, however, is to perform fracture toughness tests on a variety of regions in a weldment.

Once the target area is identified via metallurgical investigation and hardness testing, a notch orientation should be selected. The two most common alternatives
are a through-thickness notch and a surface notch, which are illustrated in Fig. 3 [15]. The size of surface notched specimens is usually $B \times B$, whereas for specimens with a through-thickness notch $B \times 2B$ is the usual geometry. The through-thickness orientation is preferable since a variety of regions in the weld can be sampled. Surface notched specimens are suitable when a particular region of the weld metal, such as the root or cap, is of interest. The specimen type should be of deeply-notched ($a/W = 0.5$) single-edge-notched bend (SENB) specimens.

For HAZ testing, the fatigue crack tip should sample a maximum amount of lower toughness zones, i.e., local brittle zones (LBZs) of the HAZ, in order to obtain a lower bound toughness value. For this reason, it is general practice to use K or 1/2K weld preparations, as shown in Fig. 4 [15]. The LBZ region(s) of the welds should be identified by micro-hardness testing and/or microstructural examination prior to the specimen preparation. A through-thickness notch should be placed on the straight side (Fig. 4). It should be noted that the total size of the LBZ at the crack tip may not correlate with the toughness value obtained. However, in general, the larger the size of the sampled LBZ, the lower is the toughness value which will be obtained.

If the purpose is to assess the significance of a particular defect in a structure, then the notch position and size ($a/W$ ranging from 0.1 to 0.5) should simulate the defect of interest. This is because the measured fracture toughness value depends on the microstructural and strength gradients in the vicinity of the fatigue crack and on $a/W$. Figure 5 shows an example of how HAZ flaws in structural welds can be simulated by test specimens [15].

3.1 Specimen Preparation, Type and Dimensions

Macro-sections

The weldments to be tested should represent the base metal, weld consumable, welding procedure and heat treatment of interest. Macro-sections of welds should be prepared to conduct metallurgical examination and hardness testing to identify the notch positions (i.e., target area) prior to extracting the fracture toughness specimens from welded plates.

Type and Dimensions

The SENB specimens widely used in fracture toughness testing of the base material are recommended. They can be plane-sided or side-grooved. The dimensions of the specimens should conform to the requirements of standard test procedures for homogeneous specimens (e.g., see [1-4]). It is recommended to use full thickness specimens ($B$ equal to the full thickness of the original welded plate) for weldment testing.
Preparation of Specimen Blanks and Notch Placement

Weld reinforcement should be removed flush with the original plate surface. In order to minimize any straightening procedure for the specimen blanks extracted from curved or distorted sections, the compact tension (CT) specimen type may be a practical option compared to the SENB specimen. When significant straightening for SENB specimens is necessary, the weld region should be kept free of any plastic deformation. Detailed procedures for straightening SENB specimens can be found in [5].

The surfaces of the specimen blank to be notched should be ground and etched to reveal the weld metal and HAZ. After identifying the target area, a line should be scribed onto the surface to mark the notch location. The machine notching procedure and dimensional requirements are the same as those for standard test procedures for homogeneous specimens. However, for narrow welds, a minimum notch width should be selected. For instance, for laser and EB welds, electro-discharge machining (EDM) with a thin wire diameter should be used (see, for instance, Fig. 6).

In order to obtain shallow cracked \( \frac{a}{W} \approx 0.1 \) SENB specimens with through thickness notch, it is recommended to use an oversized (larger \( W \)) specimen blank with longer machine notch (e.g., \( a/W = 0.3 \)). After introduction of the fatigue crack, the specimen can be machined to the required size by machining off the notched side of the specimen. This practice will help to introduce very short fatigue cracks in the target area.

The parameters, \( 2H/B \) and \( 2H/(W - a) \), affect the plastic deformation behavior of weldments [7-12]. Therefore, the values of such parameters\(^1\) for each specimen should be measured from etched specimen blanks and recorded.

3.2 Fatigue Pre-cracking

Fatigue pre-cracking should be performed for the weld specimen to be tested, i.e., no intermediate mechanical and/or heat treatment between fatigue pre-cracking and toughness testing is allowed. The maximum allowable force for fatigue pre-cracking, \( F_{\text{max}} \), of SENB specimens is given by

\[
F_{\text{max}} = \frac{B(W - a)^2}{2S} \cdot \sigma_0, \tag{1}
\]

\(^1\)A definition of \( H \) is important to evaluate the crack driving force, such as \( J \) and \( CTOD \). Recommendations given in Sec. 4 on evaluation of \( J \) and \( CTOD \) are based on idealized weld configurations, parallel sided welds. For real weld configurations such as V-, K-, or X-grooves, the definition of \( H \) is still not clear. More investigations are necessary for the adequate definition of \( H \) for such cases (see Sec. 7)
where

\[ \sigma_0 = R_{p0.2}^W \]  

for weld metal notched specimens, and

\[ \sigma_0 = \min(R_{p0.2}^W, R_{p0.2}^E) \]  

for HAZ notched specimens as well as for laser and EB steel welds with higher weld zone strength to avoid any plasticity in the weaker side of the weldments. In realistic cases, the yield strength of the HAZ, \( R_{p0.2}^{HAZ} \), is very difficult to measure. However, if it can be measured, then

\[ \sigma_0 = \min(R_{p0.2}^W, R_{p0.2}^E, R_{p0.2}^{HAZ}) \]  

should be used for HAZ notched specimens as well as for laser and EB steel welds. In case of CT specimens, \( F_{\text{max}} \) is given by [1-4]

\[ F_{\text{max}} = \frac{3}{5} \cdot \frac{B(W - a)^2}{(2W + a)} \cdot \sigma_0, \]  

The present fracture toughness testing procedures require fatigue pre-cracked specimens with restrictions on the fatigue crack front shape. To meet such requirement in weldments, a special pre-cracking procedure should be used to obtain uniform fatigue pre-crack growth across the weld thickness for specimen blanks containing welding residual stresses (as-welded and partially stress relieved specimens). The through thickness pattern of the welding residual stresses (transverse to the weld length) changes from tensile (+) stresses near the surfaces to compressive (-) ones at about mid-thickness (Fig. 7). These residual stress components act as additive stresses to the applied stresses during the cyclic loading. Therefore, during fatigue pre-cracking, compressive stresses normal to the crack plane can counteract the applied cyclic stresses and thereby decrease the magnitude of the effective stress intensity range, thus inhibiting crack growth there. However, near the side surfaces, extensive crack growth occurs due to the summation of the applied stress and the residual stress. The development of such irregular fatigue cracks may not meet the testing standard requirements for valid specimen preparation.

The process of cutting the specimen blanks from larger welded plate re-distributes the residual stresses, and thus reduces the magnitude of the residual stresses. The "as-welded" specimens should be pre-cracked and tested in this condition. Any mechanical treatment (e.g., local compression or reverse bending) prior to pre-cracking of "as-welded" specimens should not be used.

The stepwise high-\( R \) ratio procedure is recommended for through thickness notched SENB specimens for both weld metal and HAZ notches. Figure 7 shows fracture surfaces of an SENB specimen with through thickness notch and surface notch. The
fracture surface of the through thickness notch SENB \((B \times 2B)\) specimen shows the effectiveness of the stepwise high \(R\)-ratio procedure (Fig. 7a). Experience indicates that surface notched SENB specimens do not exhibit non-uniform fatigue crack front and therefore no special pre-cracking procedure is needed (Fig. 7b). A description and commentary of the stepwise high-\(R\) ratio procedure is provided below.

**Stepwise high-\(R\) ratio procedure [16,17]**

This technique consists of two \(R\)-ratio \(\left(\frac{F_{\text{min}}}{F_{\text{max}}}\right)\) levels. The basic principles of this technique are schematically shown in Fig. 8.

**Step I \((R=0.1)\)**: This first step can be used to initiate and propagate the fatigue crack to a length of about 1.0 mm. The initiation period of the fatigue crack from a machined notch will be minimized by using the full range of the applied load. During this step, a minimum or no crack growth will occur at mid-thickness of the specimen (see Fig. 7a).

**Step II \((R=0.7)\)**: In this step, the \(R\)-ratio of the cyclic loading is increased to 0.7 by keeping the same \(F_{\text{max}}\) as in the first step. This \(R\)-ratio should be used to use the improving effect on the crack front shape and to propagate the fatigue crack to the required length (see Fig. 7a). The use of \(R = 0.7\) from the beginning of the pre-cracking will increase the total time of pre-cracking considerably. Therefore, it is recommended to use \(R = 0.1\) only for the initiation stage of the fatigue crack at the machine notch tip in order to minimize the total pre-cracking time. It should be noted that a decrease of the applied stress amplitude in step II will obviously increase the time for completion of fatigue cracking.

The increased level of mean load \(F_m = \frac{F_{\text{max}} + F_{\text{min}}}{2}\), for a given \(F_{\text{max}}\) in fact prevents a possible crack tip closure at the compressive residual stress region of the specimen. The applied mean load of \(F_m\) should be high enough to keep the crack tip open at about mid-thickness region of the specimen by balancing the compressive stresses. It has been shown that in most cases using \(R = 0.5\) may not provide high enough \(F_m\) to prevent the retardation of the crack growth at the compressive residual stress region [16].

It is obvious that this technique can easily be applied to any specimen geometry and weld type on any standard testing machine without extra operation and set-up. Both local compression [18,19] or reverse bending techniques [20,21] can not practically be used for highly strength mis-matched welds, thick section high strength steels, dissimilar joints, laser and EB welds in an identical manner as well as for conventional welds and other geometries such as through-thickness notched CCT specimens. Experience also indicated that the local compression technique can result
in extensive fatigue crack growth at mid-thickness of the specimens for 1% B total
deformation for some welds. For each weld, time consuming trials are always necessary
to establish the optimum degree of local compression.

After completion of fatigue precracking, there should be no mechanical or thermal
treatment of the specimens.

4. **J-Integral Evaluation**

The J-integral is typically determined from the plastic portion of the load-load line
displacement diagrams. However, it has become apparent that it is more convenient
to determine J from the plastic portion of the load-CMOD diagram, $A_{pl}$ (Fig. 9),
particularly for welded specimens. For homogeneous specimens, J can be evaluated
from

$$J = J_{el} + J_{pl} = \frac{K^2(1 - \nu^2)}{E} + \eta_{pl} \cdot \frac{A_{pl}}{B(W-a)},$$  

(6)

with [22]

$$\eta_{pl} = 3.785 - 3.101 \left( \frac{a}{W} \right) + 2.018 \left( \frac{a}{W} \right)^2 \text{ for } 0.1 \leq \frac{a}{W} \leq 0.7,$$

(7)

or alternatively [23]

$$\eta_{pl} = 3.50 - 1.42 \left( \frac{a}{W} \right) \text{ for } 0.1 \leq \frac{a}{W} \leq 0.7.$$  

(8)

It should be noted that both Eqs. (7) and (8) provide essentially the same values of
$\eta_{pl}$ for $a/W$ ranging from 0.1 to 0.7.

4.1 **Weld Metal Crack**

For mismatched weldments, the values of $\eta_{pl}$ are affected not only by $a/W$ but
also by $M$ and $(W-a)/H$. For weld metal cracks, Wang et al. [8,9] proposed that the
$J$ estimation procedures for homogeneous specimens, Eqs. (6) and (7) or (8), would
be sufficient for the following mismatch conditions:

$$0.1 \leq \frac{a}{W} \leq 0.5 ; \quad 0.5 \leq M \leq 1.3 ; \quad \text{for all } \frac{(W-a)}{H}.$$  

(9)

The error in $J$ is less than about 10%; overestimation for overmatching, and under-
estimation for undermatching.

Even though such non-mismatch corrected procedures can provide satisfactory re-
results, more accurate $J$-estimation requires the mismatch correction, particularly for
cases outside the requirements of Eq. (9). Following the idea of Joch et al. [7], using approximate limit load solutions derived from simple arc fields, Hornet and Eripret [10,11] obtained mismatch-corrected $\eta_{pl}$ solutions for overmatched center cracked tension (CCT) and SENB specimens. The results for SENB specimens are summarized below.

$$\eta_{pl} = \left(3.50 - 1.42 \frac{a}{W}\right) + \frac{2H}{(W-a)} \cdot \frac{\sin \beta}{\sin \alpha} \cdot \frac{(1-M)}{\alpha + M(\beta - \alpha)},$$  \hspace{1cm} (10)

where

$$\alpha = \cos^{-1}\left(\cos \beta + \frac{2H}{(W-a)} \sin \beta\right),$$  \hspace{1cm} (11)

and $\beta$ has to be determined by minimizing

$$\frac{(\beta - \alpha)M + \alpha}{\beta \sin^2 \beta}.$$  \hspace{1cm} (12)

The resulting values of $\eta_{pl}$ are shown in Fig. 10. Figure 11 shows the application of their estimation procedure to experimental results for $R$-curve testing of highly overmatched ($M = 4.0$) model welds. The $R$-curve results for overmatched specimens were compared with those of the weld metal material. Information on the dimension of the specimens and material properties is shown in Fig. 11. Refer to [24] for more details on the experimental program. The non-mismatch corrected procedure provides very different $R$-curves for homogeneous and overmatched specimens, whereas the mismatch-corrected procedure provides similar $J$-$R$ curves for both specimens. Extensive validations of their procedure using FE calculations were also given for SENB and CCT specimens in [10,11]. Recently, more extensive FE validations were performed by Wang et al. [9], which showed that the procedure by Hornet and Eripret provides accurate $J$-estimation for overmatched specimens (for both shallow and deep cracks). However, it was also shown that their procedure may significantly overestimate $J$ for certain values of $(W-a)/H$, particularly for undermatched and shallow cracked overmatched specimens.

The most recent analysis on the mismatch correction of $\eta_{pl}$ solutions has been carried out at GKSS. The methodology to determine the mismatch-corrected $\eta_{pl}$ solutions is similar to that by Hornet and Eripret [10,11], but the difference lies in the use of the more accurate mismatch limit load solutions derived from slip line field and FE analyses. The closed form solutions of such limit loads are compiled in [25]. Figure 12 shows a comparison of the proposed solutions for $a/W = 0.5$ with the results from the FE analyses based on nonhardening $J_2$ flow theory. The proposed solutions agree excellently with the FE solutions, virtually for all values of $M$ and $(W-a)/H$. Since the proposed limit load solutions are in closed form, the mismatch-corrected $\eta_{pl}$ solutions can be readily evaluated [7,10,11]. Detailed information on determination of $\eta_{pl}$ solutions is given elsewhere, and only the results are shown in Fig. 12 for $a/W = 0.5$. As expected, for overmatching, the resulting values of $\eta_{pl}$ are similar to those in Fig.
11, but those for undermatching are quite different. Indeed, the results in Fig. 12 show that the difference in \( \eta_{pl} \) values for \( 0.5 \leq M \leq 1 \) is less than \( \sim 14\% \), which confirms the results by Wang et al. [9]. Moreover, the tendency of \( \eta_{pl} \)-variations with \( H/(W-a) \) also confirms their results (see Fig. 12 in [9]).

Thus the results in Fig. 12 are believed to provide accurate estimation of the mismatch effect on the \( J \)-integral for all values of \( M \) and \( (W-a)/H \). Therefore for mismatched SENB specimens with weld metal cracks, the \( J \)-integral can be accurately estimated from (6) with \( \eta_{pl} \) determined from Fig. 12.

4.2 HAZ Cracks

For HAZ cracks, the mismatch-corrected \( \eta_{pl} \) solutions can be determined in a similar manner to that for weld metal cracks, using accurate mismatch limit loads of which closed form solutions are compiled in [25]. Comparisons of the proposed limit load solutions for \( a/W = 0.5 \) with the FE results are shown in Fig. 13, together with resulting values of \( \eta_{pl} \). A notable point is that the effect of overmatching on \( \eta_{pl} \) is almost negligible, and thus the non-mismatch corrected procedures, Eqs. (6) and (7) or (8), provide sufficiently accurate \( J \)-estimation. On the other hand, the effect of undermatching is similar to that for weld metal cracks, and thus the non-mismatch corrected procedures provide \( J \) values underestimated by less than 14%.

Thus for mismatched SENB specimens with HAZ cracks, the non-mismatch corrected procedures, Eqs. (6) and (7) or (8), can provide sufficiently accurate \( J \)-estimation for overmatching, but underestimate \( J \) by less than 10% for undermatching. For undermatching, more accurate \( J \) can be determined from (6) with the mismatch-corrected \( \eta_{pl} \) values shown in Fig. 13.

5. CTOD (\( \delta \)) Evaluation

5.1 Standard CTOD Estimation Procedures

Weld Metal Cracks

Based on systematic FE analyses, Wang et al. [8,9] recommended the following \( \delta \) estimation procedures for homogeneous specimens:

\[
\delta = \frac{J}{m\sigma_Y},
\]  

(13)
where \( J \) is estimated from (6) and (7), and

\[
m = -0.111 + 0.817 \frac{a}{W} + 1.360 \frac{R_m}{R_{p0.2}}.
\]  

(14)

For mismatched specimens with weld metal cracks, they showed that the above non-mismatch corrected procedure, with \( R_m \) and \( R_{p0.2} \) being replaced with \( R_m^W \) and \( R_{p0.2}^W \), can be used for the following window:

\[
0.1 \leq \frac{a}{W} \leq 0.5 ; \quad 0.5 \leq M \leq 1.5 ; \quad \frac{2H}{W} \geq 0.2.
\]  

(15)

The error in \( \delta \) is less than 20%; underestimation for overmatching, and overestimation for undermatching.

**HAZ Cracks**

No result on the mismatch corrected CTOD estimation procedure has been reported for HAZ cracks.

Thus knowledge on the mismatch effect on CTOD in mismatched SENB specimens is quite limited. Even for the weld metal cracks, the application of the non-mismatch corrected procedure, (14), to the mismatched specimens is limited. Firstly it can not be applied to specimens with narrow welds and high mismatch levels, such as laser or EB welded specimens. Wang et al. showed that, when \( 2H/W \leq 0.2 \), the error in \( \delta \) can be quite significant even for low mismatch levels. Secondly the error in \( \delta \) by, say, 20% is not satisfactory, particularly when the estimated value of \( \delta \) overestimates the actual value. Thus mismatch and weld width corrected CTOD estimation procedures for weld metal cracks as well as HAZ cracks are in great needs. On the other hand, pending such procedures, alternative test concept can significantly simplify the problems, which is described below.

### 5.2 \( \delta_5 \) CTOD Technique

The \( \delta_5 \) CTOD technique [4,26] avoids some of the difficulties described above and may be applied to other bimaterial configurations as well as even to HAZ cracks. This technique is based on a local measurement without the need to infer from remotely measured quantities (e.g., CMOD). Figure 14 shows the gauge points used for determining \( \delta_5 \) on SENB specimens with various notch locations. However, the use of \( \delta_5 \) is not limited; it can be measured on any specimen geometry including the standard SENB specimens. The uniqueness of \( \delta_5 - R \) curves is demonstrated in Fig. 15 where \( \delta_5 - R \) curves for highly mismatched (\( M = 4.0 \) and \( M = 0.25 \)) specimens are compared with those for the corresponding homogeneous specimens [24]. Information on the dimension of the specimens and material properties is shown in Fig. 15.
corresponding \( J-R \) curves were shown in Fig. 11. The \( J-R \) curves in Fig. 11 showed significant influence of the mismatch if no mismatch correction is used. The mismatch correction is necessary to correlate \( J-R \) curves uniquely. On the other hand, the \( \delta_5-R \) curves in Fig. 15 show very limited influence of the mismatch for both overmatching and undermatching. Figure 16 shows the effect of the mismatch on HAZ toughness, in terms of \( \delta_5 \). It shows that the same HAZ exhibits increasing toughness values with decreasing \( M \) and decreasing \( a/W \).

Testing methods based on the \( \delta_5 \) technique are available [4]. Together with the \( \delta_5 \) testing technique, analytical methods to estimate \( \delta_5 \) in terms of the applied load or strain for structural components have been documented for both homogeneous specimens [25] and weldments [27]. Thus the \( \delta_5 \)-technique is an efficient method, particularly for mis-matched weldments.

6. Post Test Examination Procedures

The tested HAZ specimens should be examined for validation of the test. The weld metal half of the broken specimen should be sectioned and metallographically prepared to identify the microstructure at the fatigue crack front. Detailed information on examination procedures can be found in [5]. Figure 17 shows the sectioned two HAZ specimens with corresponding fracture surfaces. In Fig. 17b, the effectiveness of the stepwise high \( R \)-ratio fatigue precracking is again visible on the fracture surface. Sectioning perpendicular to the fracture surface across the thickness should aim the tip of the fatigue crack in order to identify the fracture initiation point and microstructure. Figure 18 shows an example for an informative post test sectioning procedure for a coarse grained heat affected zone. An optical microscope should be used for measuring the aimed brittle zone size(s) across the specimen thickness. Visual or microscopic observation of the fracture surfaces should be conducted on the second half of the broken specimen.

Significant crack path deviation may occur towards the softer part (weld or base metal depending on the mis-match level) of the specimens notched in the HAZ of conventional welds as well as for the narrow laser or EB welds. Figure 18 shows an example of crack path deviating into the base metal in a SENB specimen containing a laser weld due to very high overmatching and small \( 2H \). Such an event should be examined and information obtained from tested specimens included into the test reports. Currently at the GKSS, in the framework of Brite Euram project ASPOW, the \( CTOD \) and \( J \) testing procedures for laser and EB welds are being developed.
7. Concluding Remarks

Recommendations on toughness testing and evaluation procedures for weldments are given in this paper. For tensile and toughness testing aspects, two methods are outlined, micro-flat tensile tests and $\delta_5$ testing technique respectively. The micro-flat tensile tests are extremely useful to measure tensile properties for HAZ of thick multipass welds as well as thin section welds such as laser or EB welds. The $\delta_5$ testing technique permits direct measurement of the CTOD, of which the use is not limited and rather universal. It can be applied to any type of testing pieces as well as for structural components. These two testing methods can provide efficient tools for tensile and fracture toughness testing of materials joined by conventional as well as advanced welding technologies such as power beam welding, for instance.

For evaluation aspects, the $J$ estimation procedures for mismatched specimens are reviewed, including a summary of a new proposal for best estimates of the mismatch effect on the $J$ integral. The new procedure covers not only weld metal cracks but also HAZ cracks, which is believed to be appropriate virtually for all values of $M$ and $(W-a)/H$. Further validations and extensions to shallow cracks are in progress.

The estimation procedures for $J$ and CTOD have been extensively investigated mainly for the idealized weld configuration, parallel-sided welds. The effect of the mismatch on limit load solutions [25] showed that they are very sensitive to $(W-a)/H$ in the range of $1 < (W-a)/H < 10$. Consequently the $\eta_{pl}$ solutions for the $J$ evaluation are sensitive to $(W-a)/H$ in that range (see Figs. 12 and 13). Noticing that real weldments have rather V-, K- or X-grooves, the choice of $H$ may alter the resulting $J$ or CTOD values significantly. Even though a preliminary investigation based on 3-D FE analyses has been made for SENB and CCT specimens with V-grooves [11], more systematic investigations are needed to give a proper recommendation on the choice of $H$, particularly when the weld configuration differs significantly from the idealized (parallel-sided) one and the ligament is small ($\sim 1 < (W-a)/H < \sim 5$).

A knowledge on the effect of the mismatch on the relation between $J$ and CTOD is presently limited, and worth paying attention. Such relation could be useful, especially for $J$ and CTOD R-curve testing.

For HAZ cracks, the $J$-estimation procedures are shown to be simpler than those for the weld metal cracks, particularly for overmatched specimens. However, since the crack is located between two materials having different strengths, the intensities of plastic deformations (and thus the magnitude of the $J$ and CTOD values) are different in the base plate and the weld metal. The measured toughness values,
however, only reflect averaged values in two materials. A meaningful toughness values may be obtained only when the contribution on the measured toughness values from each material can be quantified. A preliminary investigation at GKSS indicated that the amount of the contribution depends on the mismatch ratio of the base plate and weld metal. Further investigation is necessary.
Nomenclature

\[ a \quad = \quad \text{crack length} \]
\[ A_{pl} \quad = \quad \text{plastic portion of load-CMOD diagram} \]
\[ \eta_{pl} \quad = \quad \text{plastic } \eta \text{ factor based on } A_{pl} \]
\[ B \quad = \quad \text{specimen thickness} \]
\[ E \quad = \quad \text{Young's modulus} \]
\[ F \quad = \quad \text{applied load} \]
\[ F_{\text{max}} \quad = \quad \text{maximum allowable force for fatigue pre-cracking} \]
\[ F_{YM} \quad = \quad \text{net-section yield load for mismatched specimens} \]
\[ F_{YB} \quad = \quad \text{net-section yield load for all base plate specimens} \]
\[ H \quad = \quad \text{half width of weld metal strip} \]
\[ J \quad = \quad J\text{-integral} \]
\[ J_{el} \quad = \quad \text{small scale yielding portion of } J \]
\[ J_{pl} \quad = \quad \text{fully plastic portion of } J \]
\[ K \quad = \quad \text{linear elastic stress intensity factor} \]
\[ M \quad = \quad \text{mismatch factor } (= \sigma_{YW}/\sigma_{YB}) \]
\[ n \quad = \quad \text{strain hardening exponent defined by } \epsilon/\epsilon_Y = \sigma/\sigma_Y + \alpha(\sigma/\sigma_Y)^n \]
\[ N \quad = \quad \text{strain hardening exponent defined by } \epsilon/\epsilon_Y = (\sigma/\sigma_Y)^{1/N} \]
\[ R_m \quad = \quad \text{tensile strength} \]
\[ R_{p0.2} \quad = \quad 0.2\% \text{ proof stress} \]
\[ W \quad = \quad \text{specimen width} \]
\[ \delta \quad = \quad \text{crack tip opening displacement} \]
\[ \delta_5 \quad = \quad \delta \text{ defined with } 5 \text{ mm gauge length across crack tip} \]
\[ \sigma_{YW} \quad = \quad \text{yield stress of the weld metal} \]
\[ \sigma_{YB} \quad = \quad \text{yield stress of the base plate} \]
\[ \nu \quad = \quad \text{Poisson's ratio} \]

Sub/Superscripts

\[ W \quad = \quad \text{referring to the weld metal} \]
\[ B \quad = \quad \text{referring to the base plate} \]

Acronyms

\[ \text{CMOD} \quad = \quad \text{crack mouth opening displacement} \]
\[ \text{CCT} \quad = \quad \text{center cracked tension} \]
\[ \text{CT} \quad = \quad \text{compact tension} \]
\[ \text{CTOD} \quad = \quad \text{crack tip opening displacement} \]
EB = electron beam
HAZ = heat affected zone
LBZ = local brittle zone
SEN = single edge notched bend

References


11. P. Hornet, C. Eripret and S. Hao (1997) "Experimental J evaluation from a load-CMOD curve for mismatched SENB or CCT specimens", in Mis-Matching of Interfaces and Welds (Edited by K.-H. Schwalbe and M. Koçak), GKSS Research Center Publications, Geesthacht, FRG.


Fig. 1. Standard tensile specimens for determining tensile properties of weldments.

Fig. 2. Micro-flat tensile specimens.
Fig. 3. Notch orientation of SENB specimens for weld metal testing: (a) through-thickness notch and (b) surface notch.

Fig. 4. Notch locations for HAZ testing: (a) 1/2 K-weld and (b) K-weld joint.

Fig. 5. An example how to simulate HAZ flaws in structural welds to the test specimens with simulated flaws.
Fig. 6. A machine notch produced by electro-discharge machining with a thin wire for C-Mn steel CO$_2$ laser weld SENB specimens.
Fig. 7. Schematic through thickness residual stress distribution and fracture surfaces of SENB weld metal specimens: (a) through-thickness notch and (b) surface notch. Note that for surface notch, no special pre-cracking procedure is needed.
Fig. 8. Schematic illustration of "stepwise high R-ratio" fatigue pre-cracking procedure for weldments.

Fig. 9. Definition of the plastic portion of load-CMOD curves, $A_{pl}$. 
Fig. 10. Variations of mismatch-corrected $\eta_{pl}$ solutions, according to (10)-(12).

Fig. 11. J-resistance curves of homogeneous and highly overmatched ($M=4.0$) SENB specimens [24]: (a) J evaluated without mismatch correction, and (b) with mismatch correction.
Fig. 12. Comparison of the mismatch limit load solutions [27] with the FE solutions, and the resulting mismatch-corrected $\eta_{pl}$ solutions: plane strain, weld metal crack with $a/W=0.5$. 
Fig. 13. Comparison of the mismatch limit load solutions [27] with the FE solutions, and the resulting mismatch-corrected $\eta_{pl}$ solutions: plane strain, HAZ crack with $a/W=0.5$. 
Fig. 14. Location of $\delta_5$ gauge points for weld metal crack, HAZ crack and interface crack.
Fig. 15. A uniqueness of $\delta_5$-R curves of the experimental results [24]. The corresponding J-R curves for the same experiments are shown in Fig. 11.
Fig. 16. Effect of the strength mismatch $M$ and crack length $a/W$ on HAZ toughness, measured in terms of $\delta_5$. 
Fig. 17. Sectioned HAZ SENB specimens with corresponding fracture surfaces and obtained CTOD values. The material is StE 355 steel.
Fig. 18. Fatigue crack tip microstructure revealed by post test sectioning procedure on HAZ notched SENB specimen.