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Test method for determination of the essential work of fracture of thin ductile metallic sheets

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European Foreword

This CEN Workshop Agreement (CWA 17793:2021) has been developed in accordance with the CEN-CENELEC Guide 29 "CEN/CENELEC Workshop Agreements – A rapid prototyping to standardization" and with the relevant provisions of CEN/CENELEC Internal Regulations – Part 2. It was approved by a Workshop of representatives of interested parties on 2021-05-31, the constitution of which was supported by CEN following the public call for participation made on 2020-10-26. However, this CEN Workshop Agreement does not necessarily include all relevant stakeholders.

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Introduction

Fracture toughness has shown to be a useful material property to predict formability and impact performance of metal sheets. For this reason, it has become a relevant property for sheet metal producers and stampers. However, the measurement of the fracture toughness of metallic sheets is not widely extended in the industrial sector, especially by the complexity of the Elastic Plastic Fracture Mechanics (EPFM) standardized methods (J-integral, CTOD, CTOA). Such techniques are complex and involve exhaustive specimen preparation, rigorous data treatment and the measurement of the crack advance during the tests, which is one of the main difficulties in fracture toughness measurement. Additionally, specimen geometry constraints described in some EPFM standards such as ASTM E-1820 are too restrictive and its application to thin sheets is often difficult.

In the present document, an alternative test method based on fracture mechanics to characterize the plane stress fracture toughness of thin metallic sheets is proposed, the Essential Work of Fracture (EWF) methodology. The technique has shown to be suitable to readily characterize the fracture toughness of thin advanced high strength steels (AHSS) and aluminium alloy sheets. The main advantage of the EWF methodology is the relative easiness of the tests compared to the standard methods. Currently, there is no standard test method available for the evaluation of the EWF of thin metallic sheets but a testing protocol developed by the TC4 committee (TC04- Polymers, Polymer composites and adhesives) of the European Structural Integrity Society (ESIS). However, this protocol is focused on the fracture testing of polymers and composites. Therefore, the development of a reference document for measuring the EWF of thin metallic sheets is necessary to spread the application of the method.

Other of the limiting factors that hampers the industrial implementation of fracture mechanics testing procedures is the specimen preparation. In order to obtain reliable fracture toughness values, the EWF method requires the nucleation of fatigue pre-cracks in multiple specimens, which is time consuming and makes the process more expensive. In this sense, EURECAT has developed a tool (patent Nº EP 3567364A1) to avoid fatigue pre-cracking of specimens. The tool permits to easily introduce sharp notches (notch radius similar to fatigue pre-crack) in metallic sheets with a simple shearing process. In the FormPlanet project, this new notching procedure for thin sheet specimens notching has been optimized and validated for different metallic materials. The present document describes the experimental procedure and the limitations of the proposed approach.

1 Scope

This CWA describes the procedure for the evaluation of the plane stress fracture toughness of thin ductile metallic sheets by means of the EWF methodology. The document provides the guidelines for specimen preparation, testing and data post-processing as well as the limitations of the method.

NOTE 1 The test method proposed in this document is intended to relatively thin metallic sheet materials presenting plane stress conditions, which do not fulfil the thickness requirements described in ISO 12135:2016. It is important noting that toughness values obtained by the present method are thickness-dependent. Therefore, they cannot be considered as an intrinsic material property but a geometry-independent constant for a specific sheet thickness.

NOTE 2 The recommended specimen is the Double Edge Notched Tension (DENT) because of its symmetry and minimal specimen rotation and buckling during the test. The specimens are notched, fatigue pre-cracked and tested up to fracture at a constant displacement rate. Alternatively, a mechanical notching process is described for obtaining sharp-notched DENT specimens. Investigations have shown that EWF results obtained with specimens prepared by means of this mechanical notching process are equivalent to those obtained with fatigue pre-cracked specimens for a range of AHSS. Further analysis is required to confirm the reliability of this procedure for specimen preparation in other materials of lower strength.

NOTE 3 The method requires testing multiple specimens with the same geometry but different crack lengths. From the test, two characteristic parameters are obtained; the specific essential work of fracture, w_e, and the non-essential plastic work, w_p, multiplied by a shape geometry factor β. w_e is independent of in-plane dimensions and represents the plane stress fracture toughness of thin ductile sheet materials. Since it is obtained from an average of energy values for the complete fracture, it is considered an overall resistance value to stable crack extension, i.e. it contains energetics contributions from crack initiation and propagation resistance. It is also possible determining a single initiation toughness value, w_e^i, which represents the material resistance to crack growth initiation. The parameter βw_p depends upon specimen dimensions and, therefore, it is not a material constant.

NOTE 4 Resistance to stable crack extension can be also expressed in terms of a critical crack opening displacement (δ_c). An empirical relationship between w_e, δ_c and flow properties is established.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ASTM E1820, *Standard Test Method for Measurement of Fracture Toughness*

ASTM E399, *Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials*

ISO 12135:2016, *Metallic materials — Unified method of test for the determination of quasistatic fracture toughness*

ISO 22889, *Metallic materials — Method of test for the determination of resistance to stable crack extension using specimens of low constraint*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
fracture process zone
FPZ
end region ahead of the crack tip

3.2
total work of fracture
W_f
energy obtained from integration of the area under the load-displacement curve for the complete fracture

3.3
essential work of fracture (EWF)
W_e
energy dissipated in the fracture process zone

3.4
non-essential plastic work
W_p
energy dissipated in the outer region surrounding the fracture process zone associated with plastic deformation

3.5
specific work of fracture
w_f
total fracture energy per unit area

3.6
specific essential work of fracture
w_e
energy dissipated in the fracture process zone per unit area

3.7
specific non-essential plastic work
w_p
plastic energy dissipated in the outer region surrounding the fracture process per unit volume

3.8
specific work of fracture initiation
w_f^i
crack growth initiation energy per unit area for a determined specimen

3.9
specific essential work of fracture initiation
w_e^i
initiation toughness obtained from an average of w_f^i values

3.10
critical crack opening displacement
δ_c
crack opening displacement of the end region interpreted as the load-line displacement at fracture for zero ligament length

4 Symbols and abbreviations

4.1 Symbols

a	crack length (starter notch + fatigue pre-crack)
a_o	original crack length
B	specimen thickness
B_o	original specimen thickness
b_o	original uncracked ligament length
$b_{o\,max}$	maximum original ligament length
$b_{o\,min}$	minimum original ligament length
β	geometry shape factor
δ_c	critical crack opening displacement
E	Young’s modulus
F	applied force
F_{max}	maximum force obtained from a fracture test

K	stress intensity factor
K_c	linear elastic fracture toughness
K_{max}	maximum value of K applied during fatigue pre-cracking
K_{min}	minimum value of K applied during fatigue pre-cracking
ΔK	stress intensity factor range applied during fatigue pre-cracking (K_{max}-K_{min})
L_t	specimen length
L_e	initial extensometer gauge length for load-line displacement measurement
$L_{e\,min}$	minimum initial extensometer gauge length
ρ	notch root radius
q	load-line displacement
q_f	load-line displacement at fracture
q_i	load-line displacement at initiation of propagation
$R_{p0,2}$	0,2 % offset yield strength
R_m	ultimate tensile strength
R_{AVG}	effective yield strength $\left(\frac{R_{p0,2}+R_m}{2}\right)$
r_p	radius of the plastic zone ahead of the crack tip
σ_{max}	maximum stress obtained from a fracture test calculated from the maximum force (F_{max})
σ_m	mean value of maximum stress for a set of specimens
W	specimen width
W_e	essential work of fracture
w_e	specific essential work of fracture
W_f	work of fracture
w_f	specific work of fracture
w_f^i	specific work of fracture initiation
w_e^i	specific essential work of fracture initiation
W_p	non-essential plastic work
w_p	specific non-essential plastic work

4.2 Abbreviations

AHSS	Advanced High Strength Steels
CTOA	Crack tip opening angle
CTOD	Crack tip opening displacement
DENT	Double edge notched tension
DIC	Digital Image Correlation

EDM	Electrical discharge machining
EPFM	Elastic Plastic Fracture Mechanics
ESIS	European Structural Integrity Society
EWF	Essential work of fracture
PHS	Press hardened steel

5 Background

5.1 Application of the EWF methodology and standardisation

The EWF methodology was developed by Cotterell and Reddel in 1977 [1] as an alternative method to readily characterize the fracture toughness of thin ductile metal sheets. The method has been extensively used to assess the fracture resistance of thin steel sheets [2-6] and aluminium alloys [5, 7-10]. It has been also successfully applied to evaluate the tearing resistance of ductile polymers [11-14] and more recently the methodology has shown to be appropriate to measure the fracture toughness of AHSS sheets [15-24].

Different attempts have been made to standardise the EWF methodology [25-28]. However, there is not a standard procedure developed yet. Currently, EWF tests are performed according to the testing protocol developed by the TC4 committee (TC04- Polymers, Polymer composites and adhesives) of the European Structural Integrity Society (ESIS) [25]. The last version of this protocol was revised in 2001 and it is based on a series of round robin tests during a seven-year period, with the participation of 23 laboratories. The protocol provides the guidelines for the evaluation of the EWF by using DENT specimens and discusses some of the most critical points related to specimen preparation, testing and data analysis. However, it is focused on the fracture testing of polymers and composites. Therefore, no recommendations are given about the preparation of metallic sheet specimens.

The experimental methodology described in the present document is based on the recommendations of the ESIS protocol but its applicability is extended to thin metallic sheet materials. Accordingly, recommendations about the notch preparation method are also given.

5.2 Theoretical background

The EWF methodology is based on the assumption that the total work of ductile fracture (W_f) can be separated in two terms: an essential work of fracture necessary to create new surfaces in the front of the crack tip (w_e) and a non-essential plastic work dissipated in the outer plastic region surrounding the crack plane (w_p).

In principle, the EWF can be determined from a range of specimen geometries [11] but for thin sheets the DENT specimen (Figure 1) has shown to be the most suitable because the transverse stress between the notches is tensile and there is no buckling. If the ligament is completely yielded and the plastic zone is confined to the notched ligament, then w_p is proportional to the plastic volume and w_e is proportional to the fractured area:

$$W_f = w_e b_o B_o + w_p \beta b_0^{\,2} \tag{1}$$

β is a shape factor that depends on the shape of the plastic zone, B_o is the original specimen thickness and b_0 is the original uncracked ligament length. Dividing equation (1) by the cross section area ($b_0 B_0$) allows the experimental determination of the EWF according to equation (2):

$$\frac{w_f}{b_o B_o} = w_f = w_e + w_p \beta b_o \tag{2}$$

Where w_f is the specific total work of fracture, obtained by testing the DENT specimen at a constant displacement rate, integrating the area under the load vs displacement curve (W_f) and dividing by the initial ligament area:

$$w_f = \frac{1}{b_o B_o} \int_0^{q_f} F \cdot dq \tag{3}$$

Being F the force, q the load-line displacement and q_f the load-line displacement at fracture.

Equation (2) is the equation of a straight line, where the intercept is the specific essential work of fracture, w_e, and the slope is the specific non-essential plastic work, βw_p. Thus, if a series of DENT specimens with different ligament lengths are tested and w_f is plotted against b_0, both values can be determined (Figure 2). w_e quantifies the energy dissipated within the fracture process zone during the ductile tearing process and it is a suitable parameter to describe the crack propagation resistance of thin sheets.

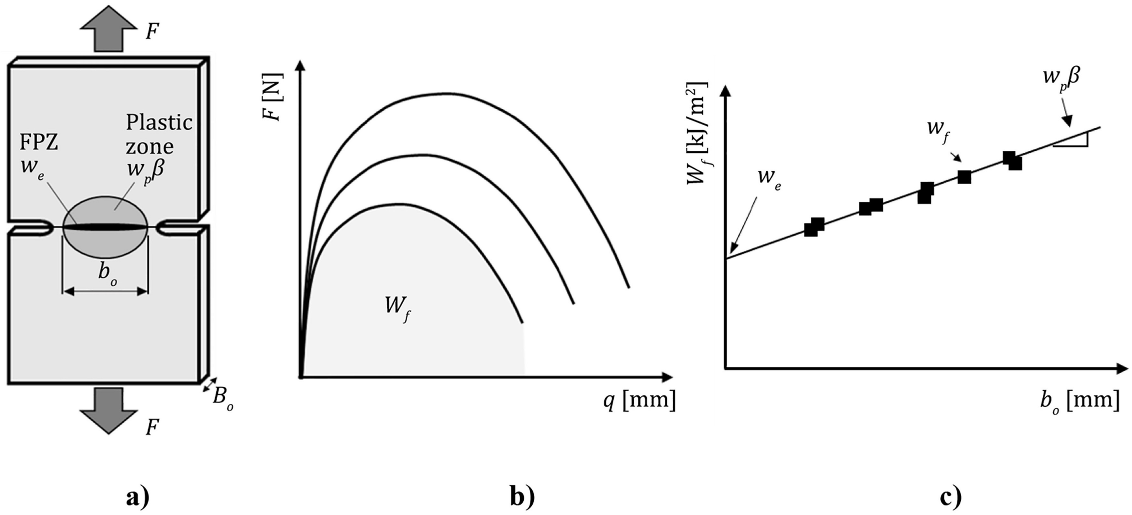
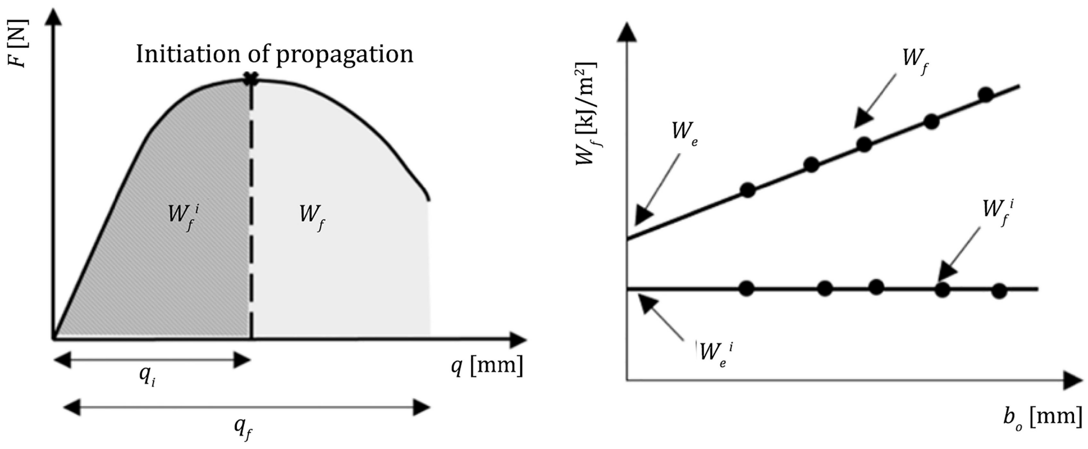


Figure 1 — DENT specimen (a) and experimental determination of the EWF: W_f for different ligament lengths (b) and plot of w_f against b_o, the intercept indicates the specific essential work of fracture, w_e (c)

The EWF methodology also permits to separate the energetic contributions from crack initiation and crack propagation. Following the methodology proposed by Mai and Cotterell [12], the fracture toughness at crack initiation, w_e^i can be obtained by calculating the w_f at the initiation of propagation (w_f^i) for different ligament lengths according to equation (4):

$$w_f^i = \frac{1}{b_o \cdot B_o} \int_0^{q_i} F \cdot dq \tag{4}$$

Where q_i is the displacement at initiation of propagation (Figure 2). Contrary to w_f, $w_f^{\,i}$ is constant and independent of the ligament length (Figure 2). Thus, only mean values of w_f^i are considered for w_e^i calculation.



a) **b)**

Figure 2 — Determination of specific work of fracture at initiation of propagation (a) and variation of w_f and $w_f{}^i$ as a function of the ligament length (b)

5.3 Influence of notch root radius on the EWF

The notch root radius, ρ, may have strong influence on EWF results [19, 22]. This effect is material dependent and, thus, the determination of a fracture toughness value for a given notch radius may not be appropriate to accurately measure the crack propagation resistance of the material. Therefore, in order to obtain reliable notch-independent toughness values, it is necessary the use of fatigue pre-cracked specimens as recommended by fracture mechanics standard procedures [29-32].

The conditions for fatigue pre-cracking are given in 7.3.1 An alternative procedure for the preparation of crack-like sharp notches in high strength metal sheets is also described in 7.3.2.

6 Test equipment and fixtures

6.1 Test apparatus

Test apparatus is required to measure the applied force and the load-line displacement throughout the fracture test. The testing machine must be equipped with a force transducer to autographically record the force applied to the specimen. The load-line displacement may be recorded automatically by an integrated measurement system or recorded digitally for processing by computer. The requirements of the system for load-line displacement are given in 6.2. Test fixtures are described in 6.3.

6.2 Measurement of the load-line displacement

Load-line displacement shall be measured by means of calibrated optical or clip-on extensometers attached to the specimen. Optical methods include video extensometry, laser-based extensometry and Digital Image Correlation (DIC).

It is not recommended to use the cross-head displacement as a measure of the load-line displacement. Experience has shown that the use of the cross-head displacement may provide inaccurate EWF results.

6.3 Test fixtures

DENT specimens shall be loaded using a suitable arrangement that ensures load train alignment between both grips as the specimen is loaded under tension. The specimen alignment is critical to ensure that the specimen is subjected only to tensile loading during all the test, and crack propagation is always under pure mode I. Torsion, buckling or any deviation from tensile stress will give rise to inaccurate results.

The clamping system can be hydraulically, pneumatically, or mechanically (bolted) assisted for opening and closing. Fixture surfaces shall have a hardness greater than 45 HRC (450 HV) or a yield strength of at least 1 000 MPa.

7 Specimen preparation

7.1 Specimen dimensions

The recommended geometry is the Double Edge Notched Tension (DENT). Figure 3 shows the characteristic dimensions of a DENT specimen for EWF testing.

A rectangle of width W and length L_t is cut from the test material. The external contour can be cut, machined or spark-eroded. W may depend on the material availability, but it is recommended to be at least three times the largest ligament length, b_o.

The distance L_t includes the initial extensometer gauge length, L_e, for load-line displacement and the gripping area. The minimum recommended initial extensometer gauge length L_e is given by equation (5):

$$L_{e\,min} = b_{o\,max} + 10 \text{ mm} \quad (5)$$

where

$L_{e\,min}$ is the minimum initial extensometer gauge length; and

$b_{o\,max}$ is the maximum ligament length.

Usually, L_e values between 25 mm and 50 mm have been used successfully.

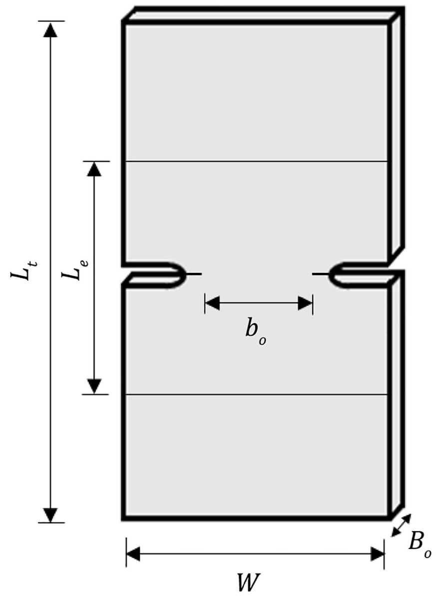


Figure 3 — Dimensions of the DENT specimen geometry

7.2 Crack plane orientation

Orientation of the crack plane in relation to product geometry shall be decided before machining and identified according to Figure 4. Three possible orientations are defined: L-T, D-D and T-L. The code used for identification is in accordance with the defined in ASTM E399. The first letter indicates the orientation of the specimen geometry with respect to the principal direction of mechanical working or grain flow. The second letter indicates the crack propagation direction.

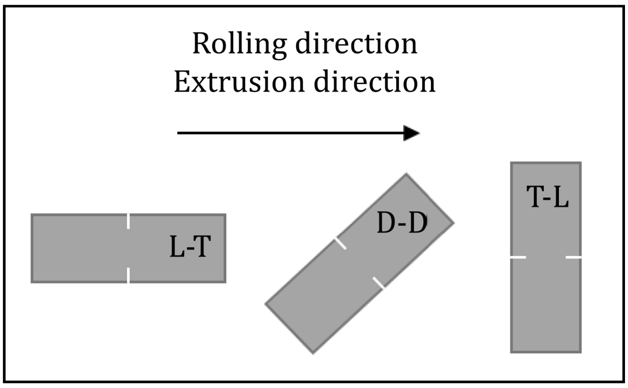


Figure 4 — Orientation of specimen geometry and crack plane with respect to the principal direction of material processing. L: longitudinal, D: diagonal, T: transverse

7.3 Specimen notching and fatigue pre-cracking

7.3.1 Fatigue pre-cracked specimens

7.3.1.1 Starter notches

For fatigue pre-cracked specimens, two symmetrical notches shall be prepared by Electrical Discharge Machining (EDM). The notch root radius (ρ) shall be not larger than 0,15 mm. Figure 5 shows an optical microscope image of the notch tip obtained by EDM. Alternative acceptable crack starter notch geometries are provided in ASTM E1820 and ISO 22889.

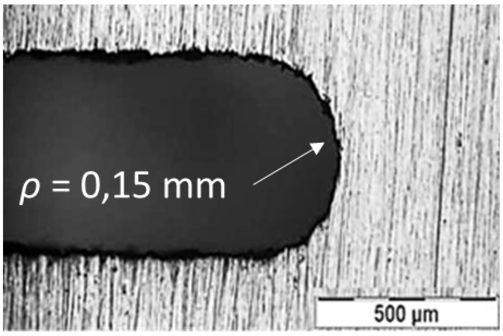


Figure 5 — Crack starter notch prepared by EDM

7.3.1.2 Fatigue pre-cracking

Fatigue cracks shall be nucleated from the root of the machined notches following the recommendations of ASTM E1820.

The fatigue tests shall be conducted under load (P) control. Tests should be run at a constant axial load ratio, $R = K_{\mathrm{min}}/K_{\mathrm{max}} = 0,1$ (tension–tension). The ΔK (K_{max}-K_{min}) should be kept below 0,3 K_c, where K_{max} and K_{min} are, respectively, the maximum and minimum stress intensity factor applied and K_c is the linear elastic fracture toughness at crack initiation. This condition should be verified after the test.

The stress intensity factor for a DENT specimen is given by [29]:

$$K = \frac{F\sqrt{\pi a}}{B_o \cdot W\sqrt{1-\frac{a}{W/2}}}\left[1,122 - 0,561\left(\frac{a}{W/2}\right) - 0,205\left(\frac{a}{W/2}\right)^2 + 0,471\left(\frac{a}{W/2}\right)^3 - 0,190\left(\frac{a}{W/2}\right)^4\right] \quad (6)$$

where

B_o is the specimen thickness;

b_o is the ligament length;

F is the actual force;

a is the crack length (notch + fatigue pre-crack); and

W is the specimen width.

The minimum fatigue crack extension shall be the larger than 0,6 mm. The crack growth may be tracked by visual inspection. To facilitate the observation of the crack advance during fatigue pre-cracking is recommended to polish the surface of the specimen in the ligament area to a mirror finish. The final crack length should be measured with the aid of an optical microscope. Due to the manual monitoring of the crack growth and the difficulty in propagating the two cracks in a perfectly symmetrical manner, the final crack length usually presents some variations from one side of the specimen to the other. A maximum crack size deviation of 0,3 mm is allowable. The final notch radius (ρ) at the crack tip shall be about 0,1 µm.

Fixtures for fatigue pre-cracking shall be carefully aligned and arranged so that loading is uniform through the specimen thickness, B_o, and symmetrical to the plane of the prospective crack. The test shall be performed at room temperature.

7.3.2 Specimens with mechanically sheared notches

For the preparation of specimens with mechanically sheared notches, a rectangular specimen with dimensions 200 mm × 55 mm (L_t × W) should be used.

The rectangular specimen shall be placed at the die and fixed using two pins (Figure 6). This fixation system ensures the alignment of the specimen and that notches are always centered respect to the pinning holes. Then, the punch shall be moved downwards and, by means of a shearing process, two crack-like sharp notches are introduced in the specimen. The obtained notch radius is approximately 2-3 µm (Figure 7).

The ligament length is modified by controlling the punch displacement. The ligament length calibration can be obtained through a previous relation made between punch displacement values and corresponding ligament lengths obtained on an initial calibration specimen.

After cutting, the punch returns to the initial position and the specimen can be extracted. Due to the shear operation, the specimen is slightly bent at the end of the process. Therefore, a final flattening operation may be desirable before tensile testing.

For this purpose, the specimen is placed in the base for specimen flattening (Figure 6a) and pressed with the blank holder. This final step is optional and it does not affect to the final result. However, it facilitates the specimen manipulation and the fitting in the testing grips.

7.4 Ligament length range

The definition of a valid ligament range is critical to obtain an accurate EWF value. The ligament should be small enough to ensure that the ligament is fully yielded before fracture but sufficiently large to ensure a global plane stress state. The lower ligament length ($b_{o\ min}$) is given by the maximum of $3B_o$ or 5 mm. This lower boundary is based on experimental observations. However, it has been shown to be adequate for most of the materials investigated in the literature.

The upper boundary is intended to avoid the spreading of the plastic zone to the edges of the specimen and to ensure that the ligament is fully yielded. According to this, the maximum ligament should be the minimum of $W/3$ or $2r_p$, where W is the specimen width and r_p is the size of the plastic zone, given by the equation (7):

$$r_p = \frac{1}{2\pi}\frac{Ew_e}{R_{p0,2}^2} \tag{7}$$

where

E is the Young modulus;

w_e is the specific essential work of fracture; and

$R_{p0,2}$ is the 0,2 % offset yield strength of the material.

As a rule, ligament lengths between 6 mm and 16 mm have shown to provide good results for a wide range of AHSS and aluminium alloys with thickness from 0,2 mm to 3,0 mm.

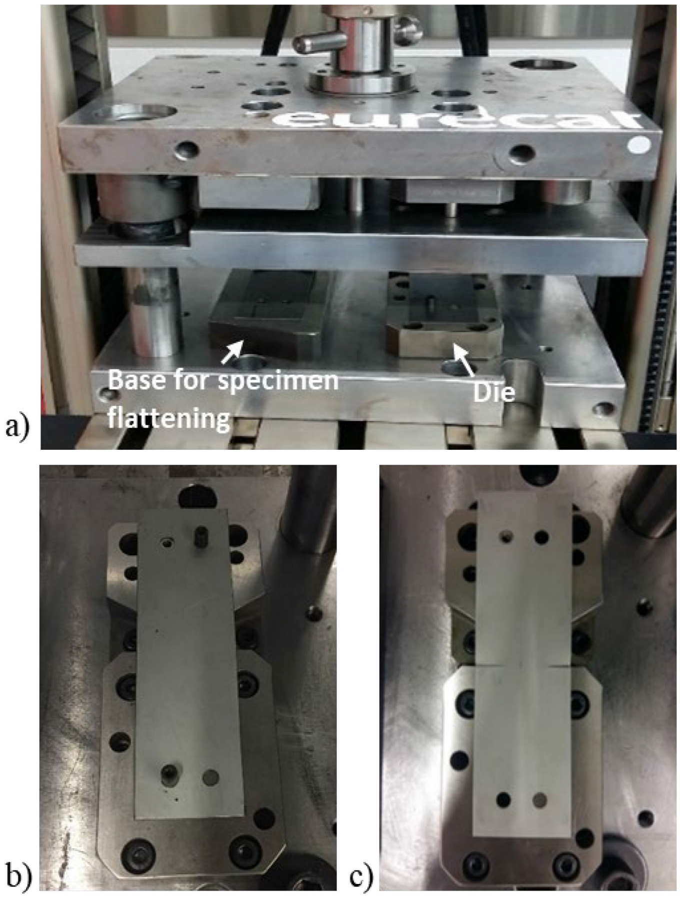


Figure 6 — (a) Detail of the cutting tool – Specimen before (b) and after (c) the notching process

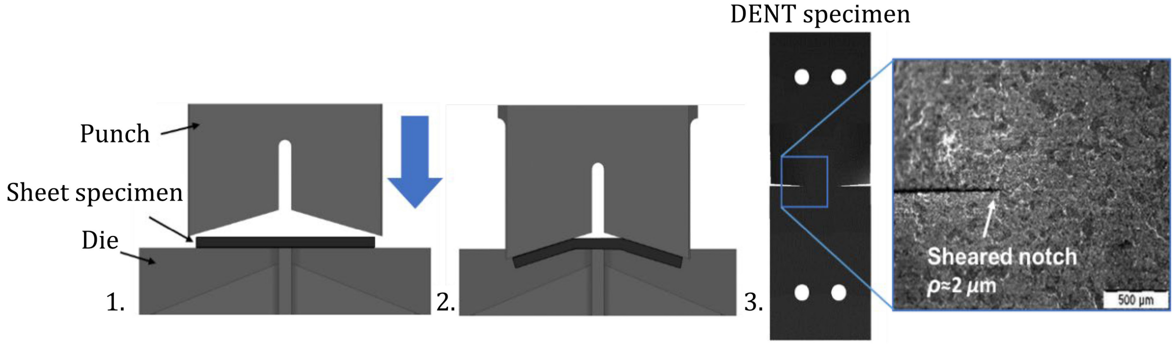


Figure 7 — Schematization of the experimental procedure for the preparation of sheared notches in sheet specimens

8 Procedure

8.1 Pre-test measurements

The dimensions of specimens shall conform to those mentioned in 7.1. Specimen thickness, B_o, and ligament length, b_o, shall be measured before the test.

The ligament length obtained after fatigue pre-cracking, b_o, shall be measured using optical equipment. The ligament length in specimens with mechanically sheared notches shall be firstly measured in both specimen sides before testing. The ligament length should be verified after testing. It is recommended to measure it from the fracture surface of a tested specimen with the aid of an optical microscope.

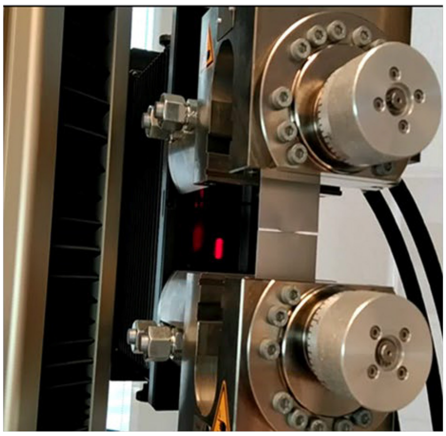
8.2 Experimental procedure

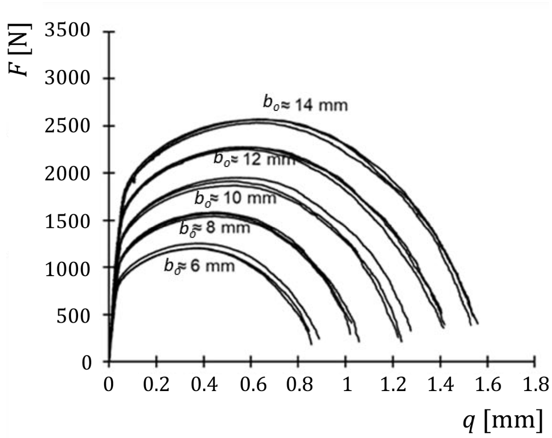
8.2.1 General procedure for EWF tests

The fracture tests shall be performed under displacement control at a constant displacement rate, sufficiently slow to ensure quasi-static conditions. Usual displacement rates of 1-2 mm/min are used for EWF testing. Fixtures for tensile tests must be aligned and arranged so that the loading is steady and symmetrical about the plane of the expected crack growth line.

The specimens shall be tested up to fracture and the force versus load-line displacement must be recorded. Figure 8 shows an example of the test of a DENT specimen in a universal testing machine and the characteristic force versus load-line displacement curves obtained for DENT specimens with different ligament lengths.

For a better accuracy on the values of w_e obtained according to this procedure, a minimum of 15 specimens is recommended to be tested. From the range of ligaments defined according to the described in 7.4, at least 5 different ligament lengths covering the whole range should be used for testing. Investigations have shown that a uniform distribution of data throughout the whole ligament range provides the best results in terms of accuracy and reliability. A minimum of 3 specimens per ligament length should be tested.





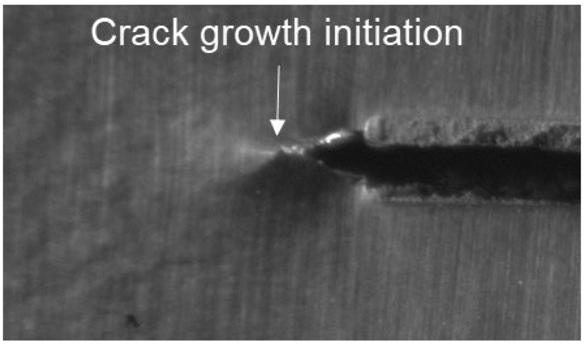
a) **b)**

Figure 8 — a) Fracture testing of a DENT specimen in the universal testing machine – b) Characteristic force (*F*) versus load-line displacement (*q*) curves obtained for DENT specimens with different ligament lengths

8.2.2 Crack growth initiation

For the determination of the crack growth initiation, different optical methods may be used. The use of a high resolution video camera or DIC equipment is recommended to record the tests and detect the initiation of crack propagation (Figure 9).

The point of crack growth initiation should be determined for a minimum of 1 specimen for each ligament length.



a) **b)**

Figure 9 — a) Digital video camera synchronized to the testing machine – b) Image corresponding to the initiation of crack propagation

9 Analysis of results

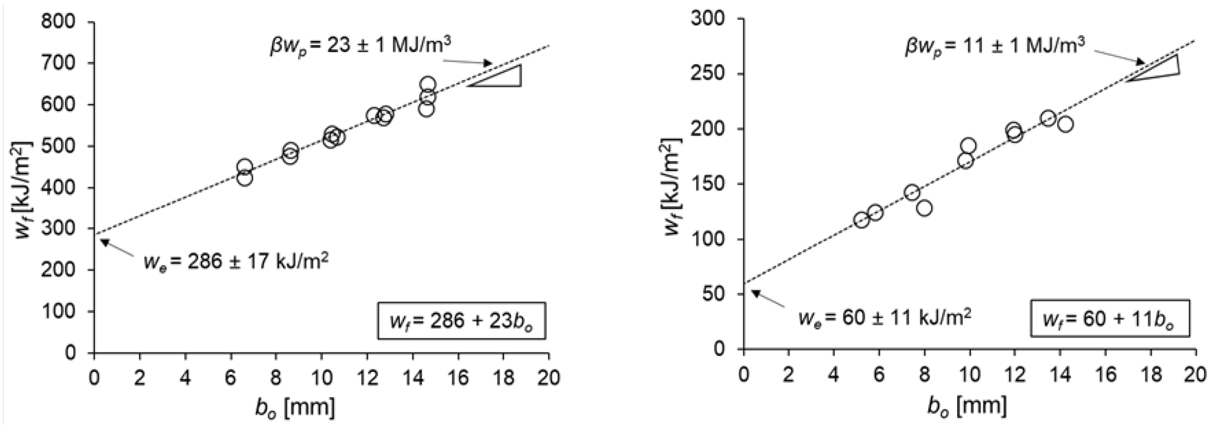
9.1 General considerations

The measurements of load and displacement are given after the experimental procedure. The values of maximum load, F_{max}, ligament length, b_o, thickness, B_o, yield strength, $R_{p0,2}$, and maximum strength, R_m, must be taken into account for the analysis of the results.

9.2 Specific essential work of fracture, w_e

From the force versus displacement data, the specific work of fracture, w_f, can be calculated according to Equation 3.

w_f values shall be plotted as a function of the ligament length and a least squares regression line must be fitted to the plotted values of w_f against b_o (Figure 10). The intercept of the linear fitting corresponds to the specific essential work of fracture value, w_e, and the slope to the plastic work, w_p, multiplied by a geometry shape factor parameter, β; as shown in 5.2. The correlation coefficient, R^2 must be also indicated.

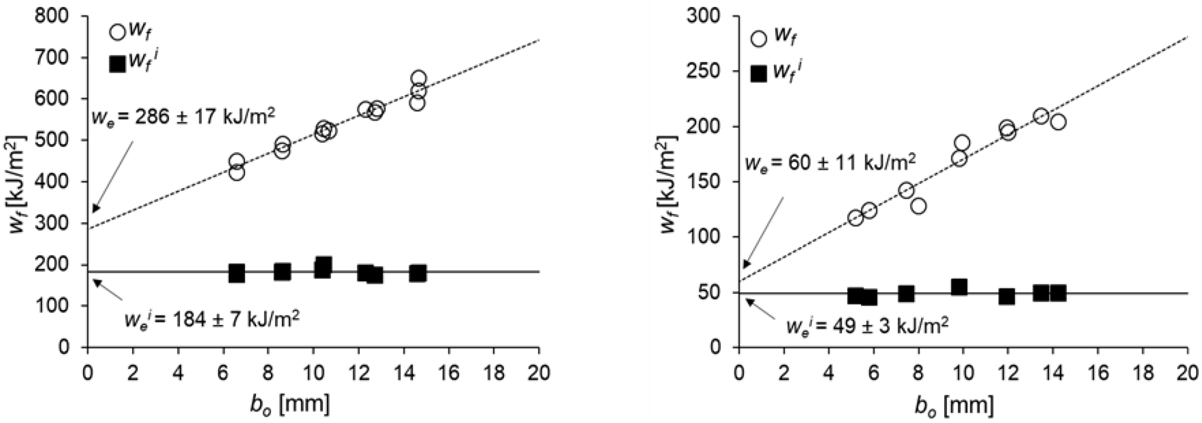


a) **b)**

Figure 10 — w_f as a function of the ligament length for: a) a dual phase steel and b) a series 6xxx aluminium alloy

9.3 Specific essential work of fracture initiation, w_e^i

w_f^i values are calculated from the area under the force versus the load-displacement curve up to the point of crack growth initiation, as indicated in 5.2. The detection of crack growth initiation shall be performed as described in 8.2.2. Fracture toughness at cracking initiation, w_e^i, is evaluated from the average of w_f^i values (Figure 11).



a) **b)**

Figure 11 — w_f (open symbols) and w_f^i (solid symbols) as a function of the ligament length – The specific essential work of fracture, w_e, and the average w_e^i are indicated – a) dual phase steel and b) series 6xxx aluminium alloy

9.4 Critical crack opening displacement, δ_c

9.4.1 Determination of the critical crack opening displacement, δ_c

For determination of the critical crack opening displacement, δ_c, the values of displacement at fracture must be plotted as a function of the ligament length as shown in Figure 12. Make a linear least squares data fitting and extrapolate the regression line to zero ligament length. The value of q_f for the zero ligament length corresponds to δ_c.

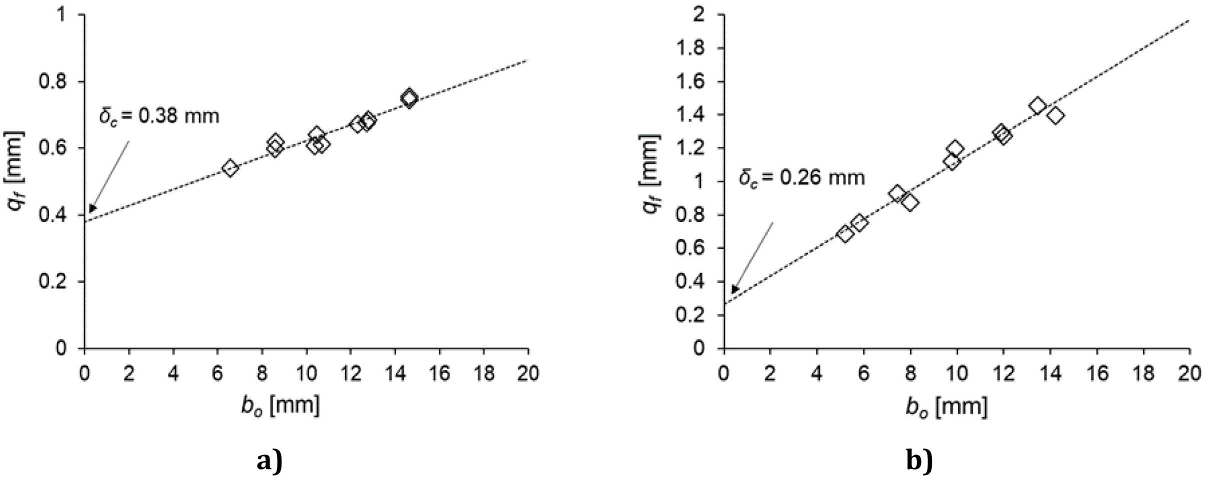


Figure 12 — q_f as a function of the ligament length and determination of the critical crack opening displacement (δ_c) at zero ligament length – a) dual phase steel and b) series 6xxx aluminium alloy

9.4.2 Relationship between we and δ_c

The relationship between the specific essential work of fracture and the critical crack opening displacement (δ_c) can be expressed as follows:

$$\delta_c = m \frac{w_e}{R_{AVG}} \qquad (8)$$

where

w_e is the specific essential work of fracture;

R_{AVG} is the effective yield strength $\left(\frac{R_{p0,2} + R_m}{2} \right)$; and

m is a material dependent on mechanical properties.

Experimental observations have shown that m is close to 1 (m≈1,05) for thin metal sheets under plane stress conditions.

9.5 Data validation criteria

9.5.1 Stress criterion

A stress criterion shall be applied to remove inconsistent data before the calculation of w_e. The stress criterion is intended to eliminate data corresponding to specimens where fracture occurs in a different stress mode or specimens showing low stress values due to premature crack growth or experimental errors.

From the maximum force (F_{max}), calculate the maximum stress (σ_{max}) according to Equation (9):

$$\sigma_{max} = \frac{F_{max}}{b_o B_o} \tag{9}$$

where

b_o and B_o are the initial ligament length and specimen thickness respectively.

Calculate the mean value of σ_{max} for all specimens, $\sigma_{m.}$ Only the specimens fulfilling the condition 0,9 $\sigma_m < \sigma_{max} <$ 1,1 σ_m shall be considered for w_e calculation (Figure 13).

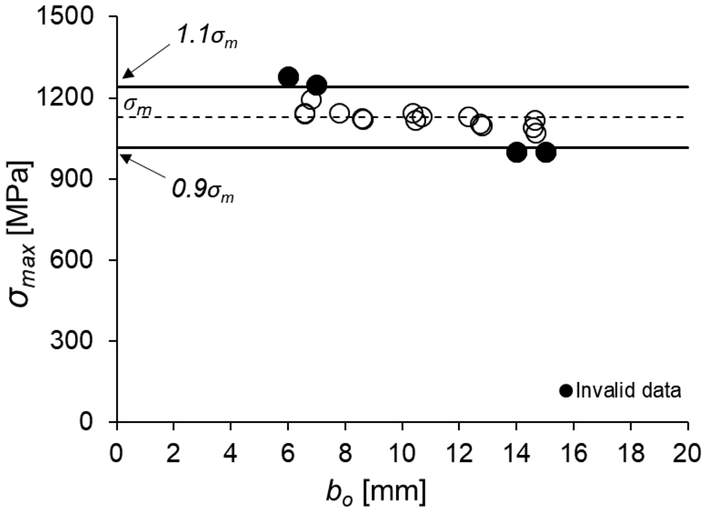
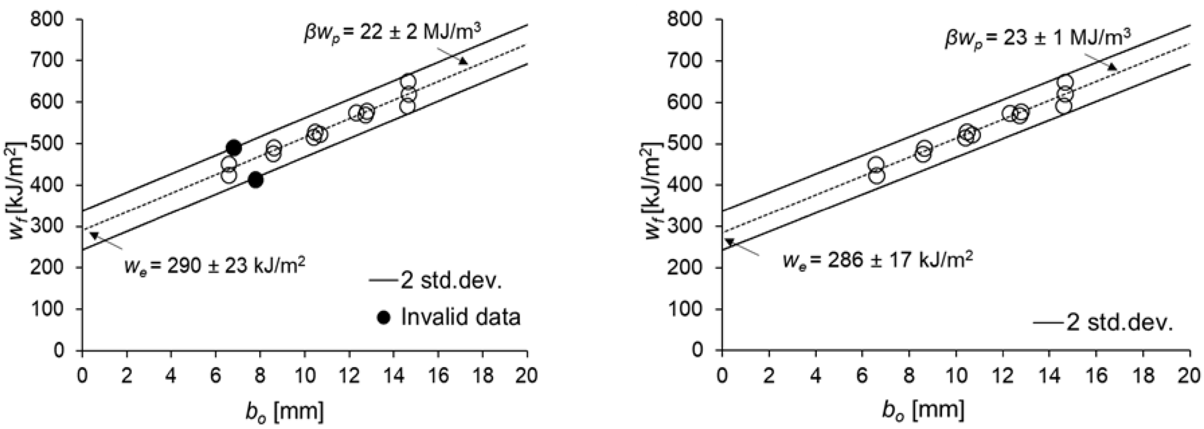


Figure 13 — Stress criterion based on an average value of σ_{max} (σ_m) – The data below 0,9 σ_m and above 1,1 σ_m are excluded for w_e calculation

9.5.2 Outlying data

An additional outlying data criterion is recommended to improve the accuracy of the measured w_e values. It is suggested to remove the data points that lie more than 2 times the standard deviation from the linear regression. After eliminating the data outliers, a final least squares regression line must be applied to the remaining w_f versus b_o data for w_e and βw_p determination (Figure 14).



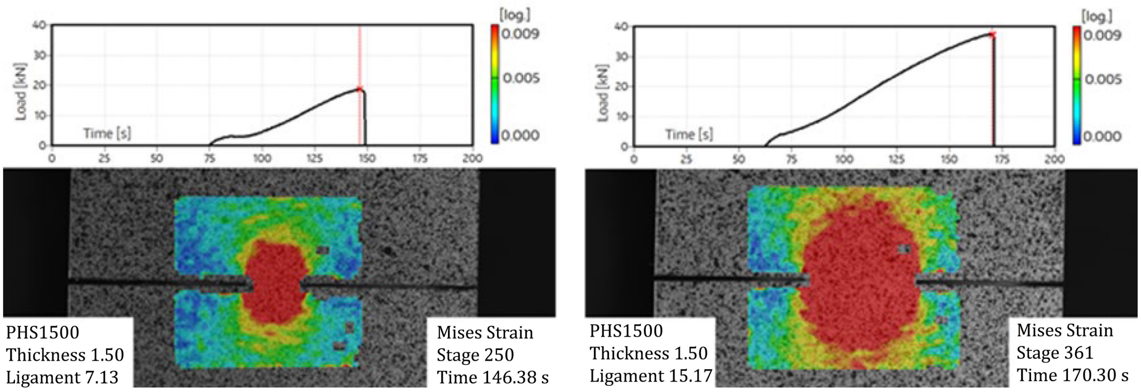
a) b)

Figure 14 — Rejection of data points that lie outside 2 times the standard deviation from the linear regression – a) before outlier data elimination, b) recalculation of w_e and βw_p after outlying data rejection

9.6 Verification of ligament yielding

One of the basic requisites for the applicability of the energy partitioning concept is that the ligament is fully yielded before fracture initiation. In order to check whether the ligament is fully yielded before crack initiation and ensure the validity of the EWF measurements, a full field strain analysis may be performed at the surface of the ligament area. For that purpose, a speckle pattern should be painted in the specimen surface and a DIC equipment should be used.

Figure 15 shows an example of the DIC analysis in the ligament area for two DENT specimens with different ligament lengths. The figure shows the Equivalent Mises Strain just before crack initiation for the smallest and the largest ligament. To validate the applicability of the EWF methodology, the plastic zone must be confined in the ligament area and the ligament must be completely yielded, as shown in Figure 15.



a) b)

Figure 15 — Full-field strain analysis in the ligament area of DENT specimens with ligament lengths of 6 mm (a) and 15 mm (b)

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