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## New tool to evaluate the fracture resistance of thin high strength metal sheets

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# New tool to evaluate the fracture resistance of thin high strength metal sheets

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**Abstract.** Fracture toughness has become a key property to predict the fracture performance of high strength metal sheets (edge cracking resistance, crash failure behaviour, local formability, etc.). However, the measurement of the fracture toughness of thin sheets still being challenging, mainly because of complex, expensive and time-consuming specimen preparation. In this work, an innovative tool to readily assess the fracture resistance of thin advanced high strength metal sheets is presented. The device consists of a special cutting tool (punch and die) designed to introduce sharp notches in sheet specimens through a simple shearing process. This new method avoids the need for fatigue pre-cracking procedures and allows measuring the fracture toughness of thin metal sheets with easy and cheap specimen preparation. It has been used in this work to evaluate the crack propagation resistance of four different advanced high strength steel sheets. The obtained toughness values are in good agreement with those measured with fatigue pre-cracked specimens and they show to be suitable to predict edge formability of AHSS sheets.

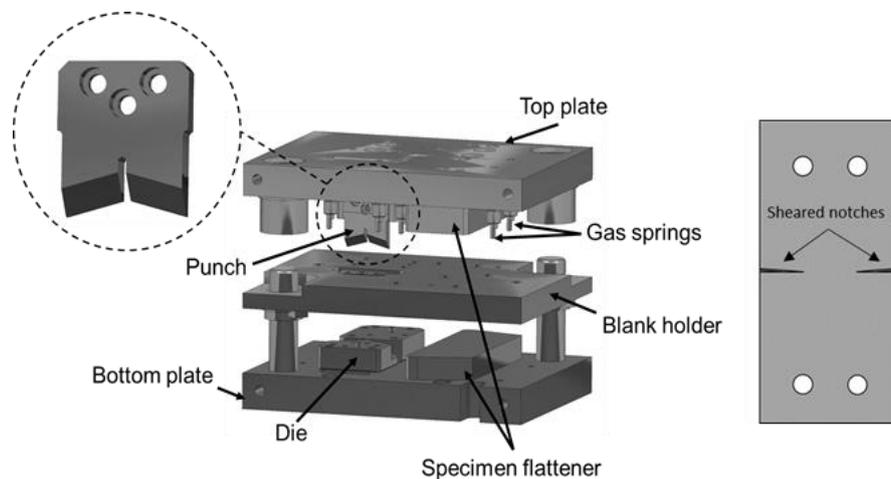
## 1. Introduction

Recent developments in new high strength sheet materials for automotive lightweight construction has brought new challenges to the sheet manufacturing sector: the need for accurate characterization techniques and methods to avoid sheet cracking occurrence during forming and to predict in-service performance. The high strength and limited ductility of such alloys increase their cracking susceptibility and reduce their formability. Thus, end-use industries and their suppliers are currently facing serious productivity losses due to the occurrence of unexpected fractures during forming. Moreover, end-users are continuously asking for high-performance materials and reliable methods to predict crashworthiness in the transport sector and long-life performance in other engineering applications. In this regard, fracture toughness measured in the frame of fracture mechanics has shown to be a suitable material property to understand crack-related problems in high strength metal sheets [1-5]. Unfortunately, the experimental evaluation of fracture toughness in thin sheets is not straightforward. It involves tedious specimen preparation, including expensive and time-consuming fatigue pre-cracking operations, and complex crack growth measuring techniques. Furthermore, the thickness of these sheets (usually 1-3 mm), do not satisfy the size requirements described in fracture mechanics standard procedures [6,7]. As a consequence, the knowledge of the fracture properties of such high strength sheet materials is very limited.

The Essential Work of Fracture (EWF) methodology [8] has shown to be a suitable alternative to readily characterize the fracture toughness of such thin high strength metal sheets [2-5, 9]. The method is very simple and does not require the measurement of the current crack advance during the test, which



supposes great advantage respect to traditional elastic-plastic fracture mechanics (EPFM) procedures. However, as it is well known in fracture mechanics testing, EWF measurements are strongly affected by the notch root radius [9]. Therefore, to obtain reliable notch-independent toughness values, it is necessary the use of fatigue pre-cracked specimens as recommended by standard procedures [6, 7]. This significantly increases the cost and time of the tests. Moreover, specialized equipment and skilled staff are required. To overcome such experimental difficulties in specimen preparation for fracture toughness characterization of thin metal sheets and to promote its application as routine testing for quality control and material selection, an innovative tool is presented in this work. The device, developed at the Unit of Metallic and Ceramic Materials of Eurecat and registered under European patent EP 3567364A1, consists of a two-pillar modular cutting die, equipped with a bevelled punch (Figure 1 left) designed to introduce crack-like sharp notches in the sheet specimens. The tool allows obtaining rectangular Double Edge Notched Tension (DENT) specimens (Figure 1 right) by means of a simple shearing process. It works with sheet blanks between 0.5 and 2 mm thickness approximately (its application to thicknesses above 2 mm is under study). In the present work, the new device has been used to evaluate the EWF of 4 different Advanced High Strength (AHSS) sheets of 1000-1200 MPa strength and  $\approx 1.4$  mm thickness. In order to validate the obtained fracture toughness results, they are compared to those obtained with conventional fatigue pre-cracked specimens.



**Figure 1.** Left: Tool for introducing sharp notches in sheet metal specimens and detail of the bevelled punch. Right: DENT specimen with sheared sharp notches

## 2. Materials and methods

### 2.1. Materials

The materials investigated in this work are 4 AHSS grades in the form of 1.35-1.4 mm thickness sheets. The steels are a Complex Phase (CP) steel, two Dual Phase (DP) steels and a 3rd GEN Transformation Induced Plasticity (TRIP)-assisted steel. The mechanical properties of the studied steels for the transverse direction are indicated in Table 1. Sheet thickness is also given. CP steel has a homogeneous bainite/tempered martensite matrix and it is characterized by low strain hardening and high yield stress to tensile strength ratio. DP-A has a ferritic-bainitic matrix with some amount of tempered martensite and a lower amount of hard martensite islands. It shows higher strain hardening and greater elongation values than CP steel. DP-B has a more homogeneous ferrite-martensite distribution. It shows slightly lower elongation than DP-A and higher strain hardening than CP. The microstructure of the 3rd Gen TRIP-assisted steel consists of a bainitic matrix with islands of martensite/retained austenite. It has a considerable amount of retained austenite ( $\approx 15\%$ ). The strain-induced transformation of retained austenite to martensite (TRIP effect) enhances strain hardening and elongation values (both uniform and total).

**Table 1.** Mechanical properties of the investigated materials for the transverse direction

Material	Thickness, $t$ [mm]	Yield strength, $\sigma_{ys}$ [MPa]	Ultimate Tensile Strength, $\sigma_{UTS}$ [MPa]	Uniform elongation, $A_g$ [%]	Elongation at fracture, $A_{80}$ [%]	Strain hardening exponent, $n$ 2-4%
CP	1.4	915	1008	4.8	8.8	0.05
DP-A	1.35	807	1057	6.6	9.6	0.13
DP-B	1.4	769	1040	5.3	8.7	0.09
3 <sup>rd</sup> Gen	1.4	987	1216	9.2	12.6	0.11

## 2.2. Fracture toughness measurements: Essential Work of Fracture methodology

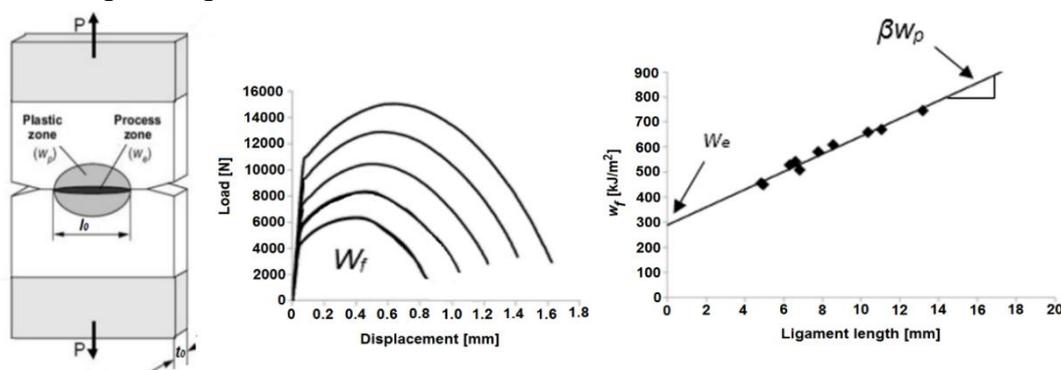
The Essential Work of Fracture (EWF) methodology was developed to quantify the ductile tearing resistance of thin ductile metal sheets [8]. The methodology permits to separate the total work of ductile fracture ( $W_f$ ) in two energetic contributions: an essential work of fracture ( $w_e$ ), developed in the fracture process zone and necessary to create new surfaces in the front of the crack tip and a non-essential plastic work ( $w_p$ ) surrounding the fracture area. The first term is proportional to the fracture surface and the second to the plastic volume, according to:

$$W_f = w_e l_0 t_0 + w_p \beta l_0^2 t_0 \quad (1)$$

where  $l_0$  is the ligament length (the non-fractured section between the two edge notches, see Figure 2),  $t_0$  is the specimen thickness and  $\beta$  is a shape factor that depends on the shape of the plastic zone. Even though different specimen geometries can be used to obtain the EWF, the DENT specimen has shown to be the most suitable geometry for thin sheets since there is no buckling during the test. The experimental procedure for the determination of the EWF is schematized in Figure 2.  $W_f$  is obtained by testing a DENT specimen (Figure 2 left) up to fracture at a constant displacement rate and integrating the area under the load vs displacement curve. The specific work of fracture ( $w_f$ ) is obtained by dividing  $W_f$  by the initial ligament area  $l_0 t_0$ . Thus, equation (1) can be rewritten as:

$$\frac{W_f}{l_0 t_0} = w_f = w_e + w_p \beta l_0 \quad (2)$$

If DENT specimens with different ligament lengths are tested and  $w_f$  is plotted against the ligament length  $l_0$ , a straight line with a positive intercept, which is the specific essential work of fracture ( $w_e$ ), is obtained (Figure 2 right).

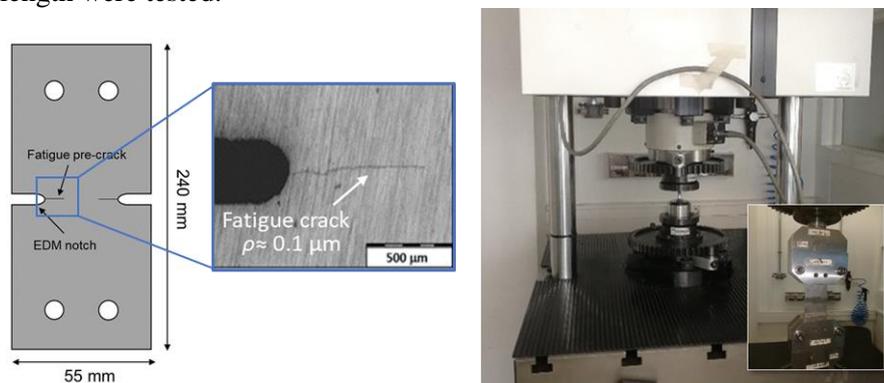


**Figure 2.** DENT specimen and experimental determination of the EWF:  $W_f$  for different ligament lengths ( $l_0$ ) and plot of  $w_f$  against  $l_0$ . The y-intercept indicates the specific essential work of fracture,  $w_e$  [4].

### 2.3. Specimen preparation

In the present work, EWF tests have been performed with two different notch configurations: 1) fatigue pre-cracks according to standard procedures recommendations and 2) mechanically sheared notches obtained with the new tool. The experimental procedure for the preparation of both notch conditions is described in *Section 2.3.1* and *2.3.2*.

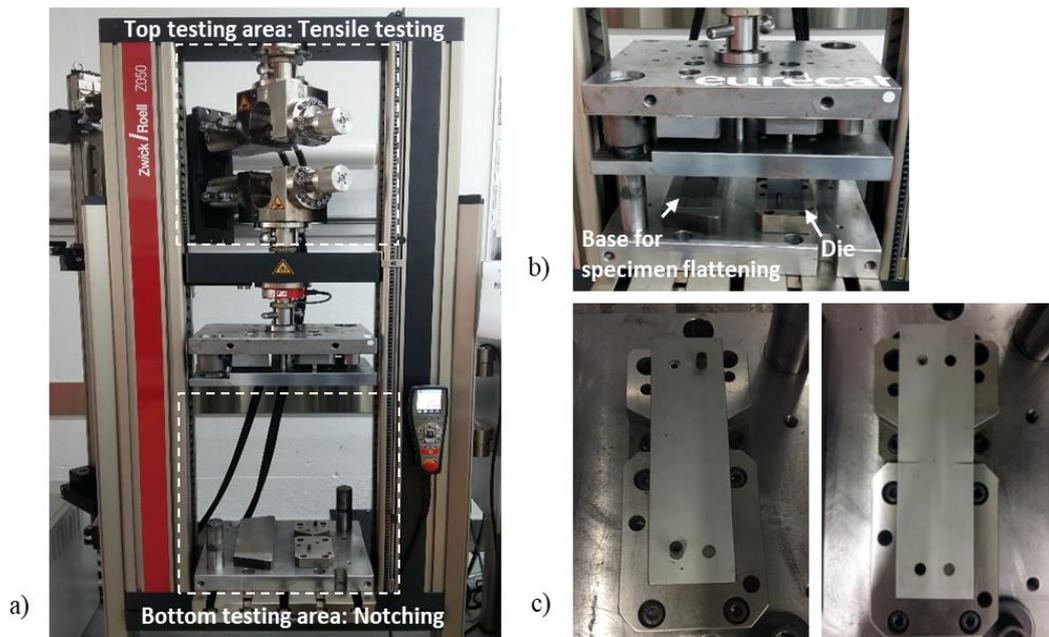
**2.3.1. Fatigue pre-cracked specimens.** For EWF tests with fatigue pre-cracked specimens, rectangular DENT specimens of 240 x 55 mm were used (Figure 3 left). Initial notches were machined by electrical discharging machining (EDM). Then, fatigue pre-cracks were nucleated at the notch root following the recommendations of the ASTM E1820 standard [7]. For fatigue pre-cracking, a resonance fatigue machine was used (Figure 3 right). The cracks were extended about 1-1.5 mm per side. All the specimens were machined at transverse orientation respect to the rolling direction. The final notch radius ( $\rho$ ) at the crack tip is approximately 0.1  $\mu\text{m}$ . Ligament lengths ( $l_0$ ) from 5 to 15 mm were used and 3 specimens per ligament length were tested.



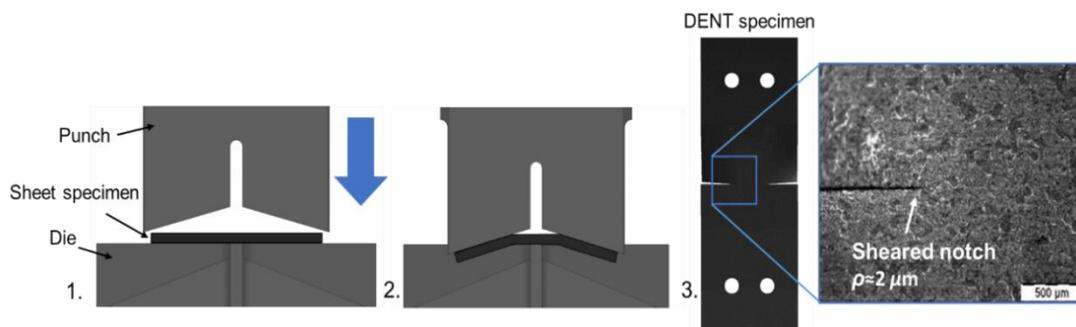
**Figure 3.** Left: DENT specimen and detail of the fatigue pre-crack. Right: Resonance fatigue machine.

**2.3.2. Specimens with sheared notches.** The new notching device (Figure 1) was used to prepare DENT specimens with different ligament lengths. Figure 4 shows some images of the experimental setup. The tool was mounted in a Zwick Roell 50 kN AllroundLine testing machine. The machine has two working areas, which permits to perform the notching and the subsequent tensile testing with a single testing equipment and easily switch from one operation to another (Figure 4a). The experimental procedure for specimen notching is schematized in Figure 5. The process is described as follows: first, a rectangular specimen of 200 x 55 mm (cut at transverse orientation respect to the rolling direction) is placed at the die and fixed using 2 pins (Figure 4c). This fixation system ensures the alignment of the specimen and that notches are always centred respect to the pinning holes. Then, the punch is moved downwards and, by means of a shearing process, two sharp notches (notch radius,  $\rho \approx 2 \mu\text{m}$ ) are introduced in the specimen (notches symmetrical respect to the longitudinal axis of the specimen). The ligament length is modified by controlling the punch displacement, i.e. the greater the punch displacement the smaller the ligament between the two notches. After cutting, the punch returns to the initial position and the specimen can be extracted. Due to the shearing operation, the specimen is slightly bent at the end of the process. Therefore, a final flattening operation is performed before tensile testing. The specimen is placed in the base intended for that purpose (base for specimen flattening, Figure 4b) and pressed with the blank holder. This final step is optional and it does not affect the final result. However, it is highly recommendable since it facilitates the specimen manipulation and the fitting in the testing grips.

Due to the difficulty of measuring the length of the ligaments directly on the specimen, they were measured from the fracture surface after testing. Ligament lengths ( $l_0$ ) from 8 to 20 mm were obtained and 2 specimens per ligament length were used. In total, 8 to 12 specimens per material were tested.



**Figure 4.** Images of the experimental setup for the notching process. a) Setup of the tool in the testing machine. b) Detail of the cutting tool. c) Specimen before (left) and after (right) the notching process.



**Figure 5.** Schematization of the experimental procedure for the preparation of sheared notches in sheet specimens.

#### 2.4. EWF tests

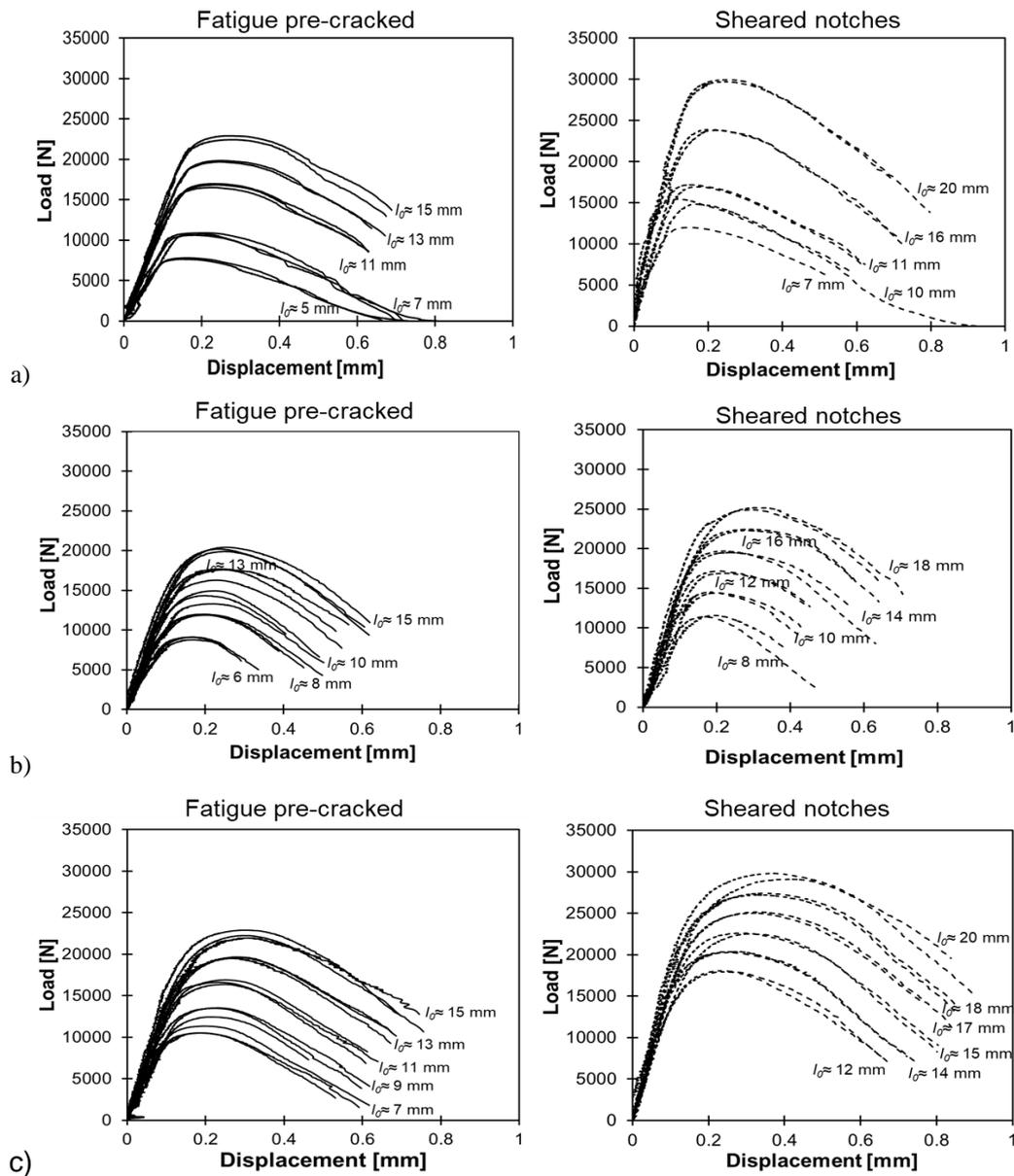
After notch preparation, the DENT specimens were tested up to fracture according to the European Structural Integrity Society (ESIS) protocol for EWF testing [10]. The tests were conducted at a constant displacement rate of 1 mm/min. The load-line displacement was measured by means of the video extensometer using initial extensometer marks separated 25 mm.

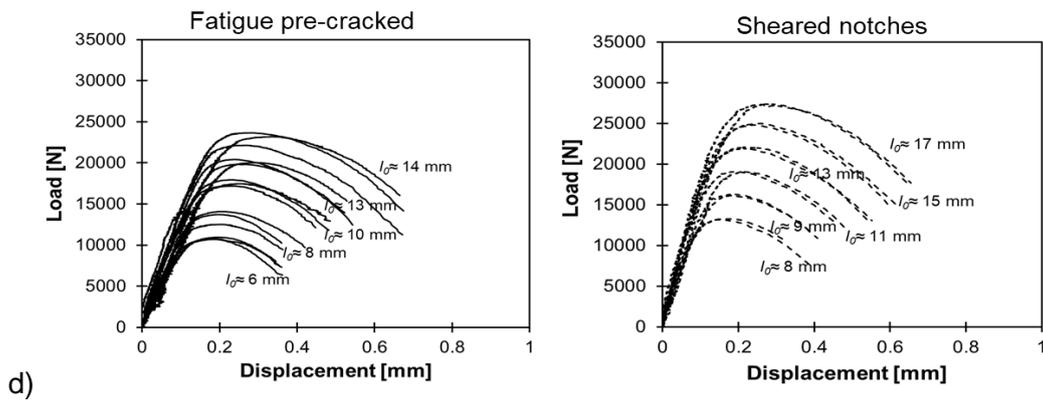
### 3. Results and discussion

#### 3.1. EWF results

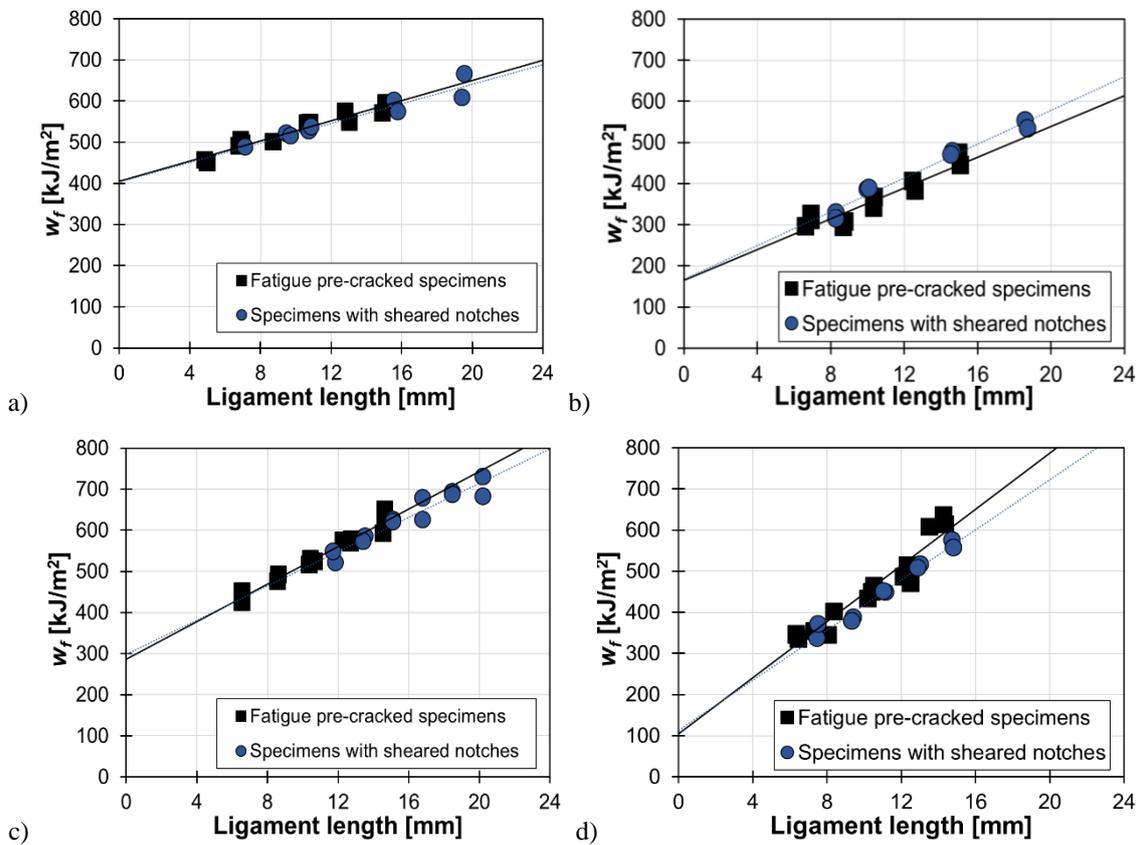
Figure 6 shows the load vs load-line displacement curves for the two specimen configurations. Figure 7 plots the values of  $w_f$  as a function of the ligament length. Numerical values of  $w_e$  and  $\beta w_p$  are given in Table 2 and Figure 8. As observed, for the same ligament length, both fatigue pre-cracked and sheared specimens show very similar load vs displacement curves (similar maximum load and displacement at fracture) in the four investigated materials. It explains the good agreement between  $w_f$  values for the two notch conditions (Figure 7) and the practically identical specific essential work of fracture,  $w_e$  and plastic work,  $\beta w_p$  (Figure 8). In general, very good repeatability is observed for sheared specimens, which

enhance the reliability of the obtained toughness values and confirms the robustness of the new process. It is worth noting that the similarity between specimens of the same ligament length is improved in sheared specimens. This is because the notch length is precisely defined by the punch displacement and, therefore, is easier to obtain multiple specimens with the same ligament. On the other hand, the ligament size in fatigue pre-cracked specimens is determined by the length of the fatigue cracks, which makes difficult to have two specimens with identical ligament.





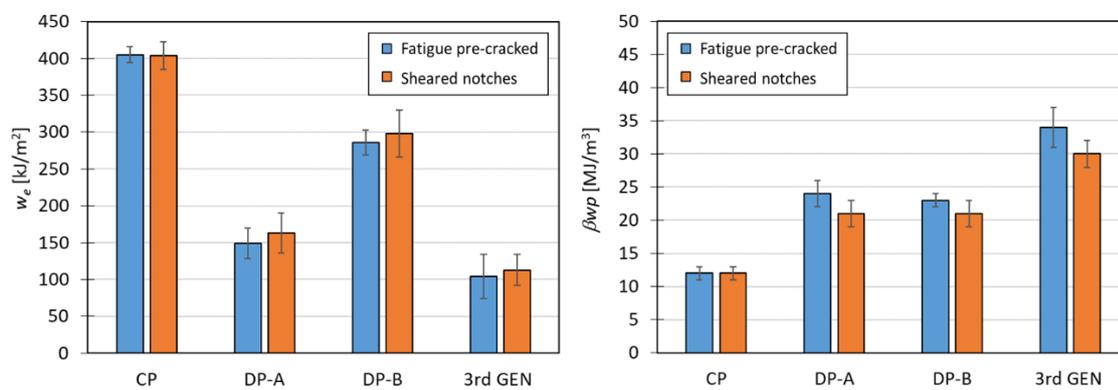
**Figure 6.** Load-displacement curves obtained from EWF tests with fatigue pre-cracked specimens (left) and specimens with sheared notches (right). a) CP, b) DP-A, c) DP-B and d) 3rd Gen AHSS.



**Figure 7.**  $w_f$  values against ligament length for the two investigated specimen configurations. a) CP, b) DP-A, c) DP-B and d) 3rd Gen TRIP-assisted.

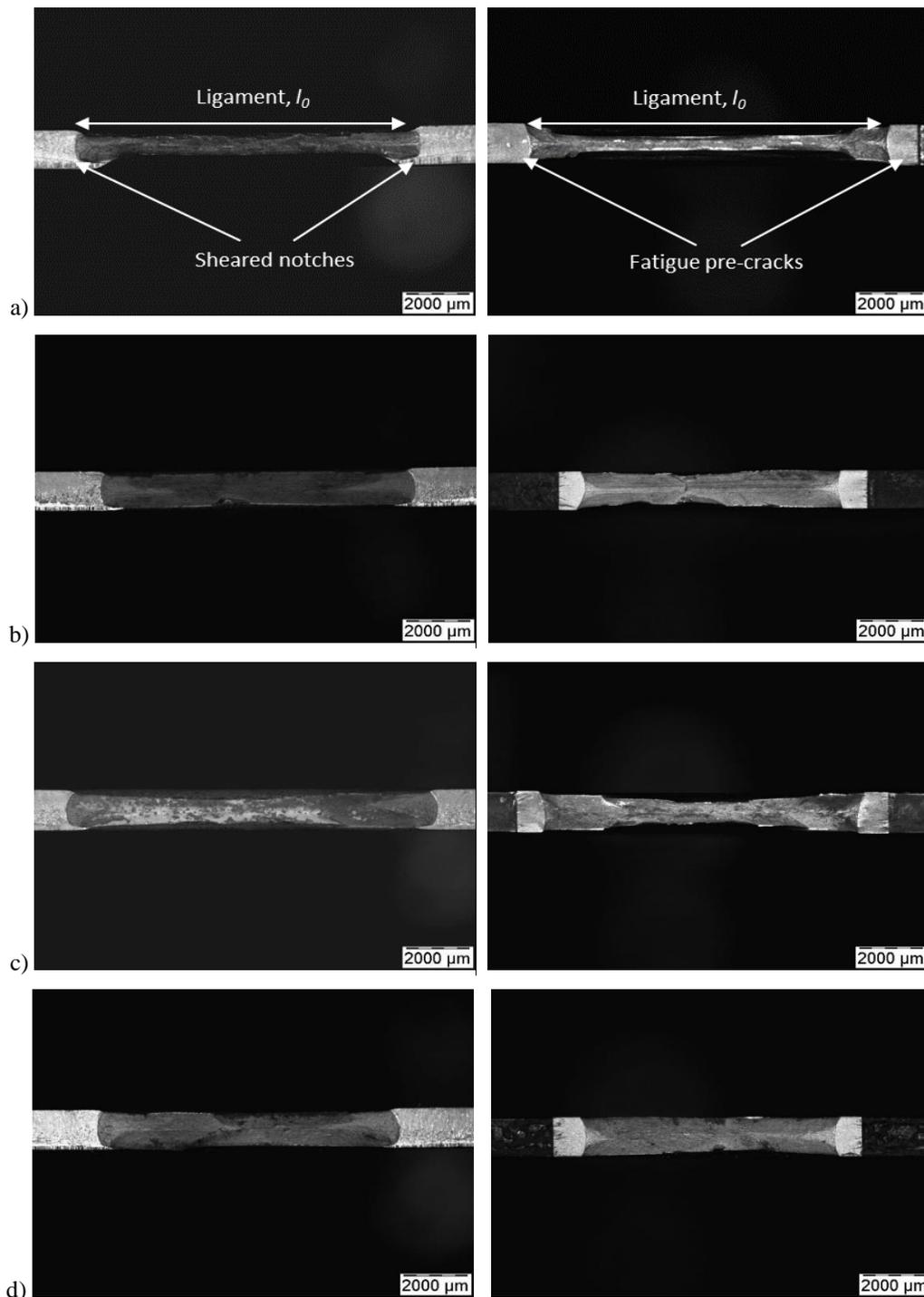
**Table 2.** EWF results obtained with fatigue pre-cracked specimens and specimens with sheared notches

Material	<i>Fatigue pre-cracked</i>		<i>Sheared notches</i>	
	$w_e$ [kJ/m <sup>2</sup> ]	$\beta w_p$ [MJ/m <sup>3</sup> ]	$w_e$ [kJ/m <sup>2</sup> ]	$\beta w_p$ [MJ/m <sup>3</sup> ]
CP	405 ± 11	12 ± 1	404 ± 19	12 ± 1
DP-A	149 ± 21	24 ± 2	163 ± 27	21 ± 2
DP-B	286 ± 17	23 ± 1	298 ± 32	21 ± 2
3 <sup>rd</sup> GEN	104 ± 30	34 ± 3	113 ± 21	30 ± 2

**Figure 8.** Results from EWF tests with fatigue pre-cracked (blue) and sheared (orange) specimens. Left: specific essential work of fracture,  $w_e$ . Right: non-essential plastic work,  $\beta w_p$ .

### 3.2. Fracture surface of DENT specimens

Figure 9 shows the fracture surfaces of different sheared and fatigue pre-cracked DENT specimens. It can be observed that for both specimen configurations the fracture aspect is quite similar and the ligament is well defined between the two notches. The major difference between the two notch types is the shape of the crack front (concave for the sheared notch and convex for the fatigue pre-crack). Overall, it was found that the morphology of the sheared notches is similar in the four investigated AHSS grades and independent of the ligament length.

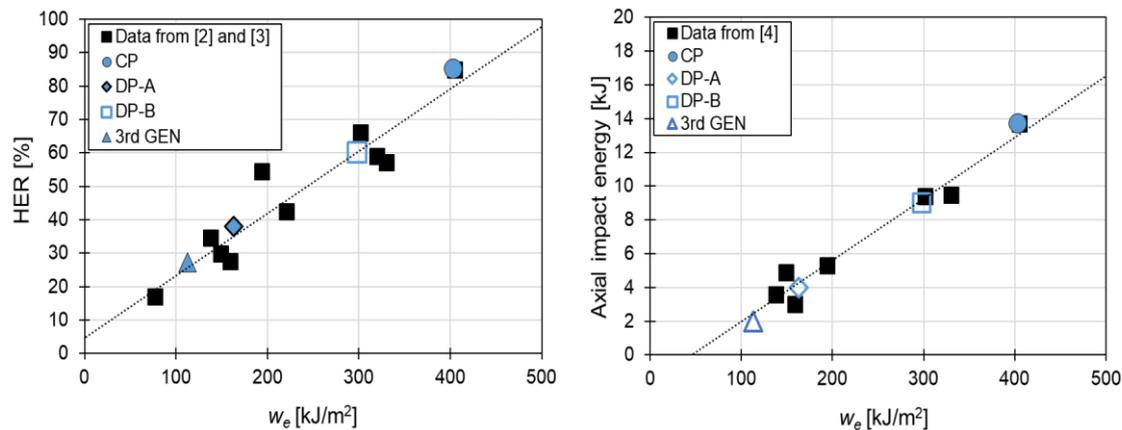


**Figure 9.** Fracture surfaces of DENT specimens with sheared notches (left) and fatigue pre-cracks (right). a) CP, b) DP-A, c) DP-B and d) 3rd GEN. The different areas (fractured ligament, sheared notch and fatigue pre-crack) are indicated in the first images.

#### 4. Applications

As mentioned before, fracture toughness has shown to be a useful material property to predict crack-related problems in high strength metal sheets, such as edge fractures [1-3], crack formation during crash [4] or other fractures related to their local ductility [5]. It is illustrated in Figure 10, where  $w_e$  values of several AHSS grades are plotted against HER [2-3] and the maximum energy absorbed in axial crash tests [4]. As already discussed in [2-5],  $w_e$  shows a very good correlation with HER and crash resistance.

Therefore,  $w_e$  can be used to estimate the fracture resistance of AHSSs and predict their cracking behaviour during forming or crash. According to the linear data fittings depicted in Figure 10, expected values of HER and impact energy for the steel grades investigated in this work are plotted as a function of the obtained specific essential work of fracture values (results from EWF tests with sheared specimens). In the case of DP-A and 3<sup>rd</sup> GEN steel, the HER was experimentally evaluated according to ISO16630. As observed, the measured HER fits very well in the linear  $w_e$  vs HER data fitting, which validates the suitability of  $w_e$  for edge cracking resistance prediction. Therefore, the new testing procedure presented, can be used as a fast and cost-effective tool to readily assess the fracture performance of AHSS sheets.



**Figure 10.** Correlation of  $w_e$  with HER (left) and axial impact energy (right). The data represented by black squares is extracted from references [2-4]. Blue symbols correspond to  $w_e$  values obtained in this work. Solid symbols represent experimentally evaluated values of HER and axial impact energy. Open symbols are expected values according to the linear data fitting (dashed line).

## 5. Conclusions

In the present work, an innovative device to prepare high strength metal sheet specimens for fracture toughness characterization has been presented. The tool can be easily mounted in a universal testing machine and offers an easy and cheap alternative to fatigue pre-cracking procedures. The new process has shown to be robust and reliable enough to evaluate the fracture toughness of four different AHSS sheets. It supposes a great time-saving in specimen preparation and it can be very useful to boost the use of fracture toughness measurements as routine testing for coil quality determination or for the selection of high strength sheet materials with enhanced cracking resistance.

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