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A new cracking resistance index based on fracture mechanics for high strength sheet metal ranking

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A new cracking resistance index based on fracture mechanics for high strength sheet metal ranking

D. Frómeta[1], S. Parareda[1], A. Lara[1], L. Grifé[1], I. Tarhouni[1] and D. Casellas[1,2]

[1] Eurecat, Centre Tecnològic de Catalunya, Unit of Metallic and Ceramic Materials, Plaça de la Ciència, 2, Manresa 08243, Spain

[2] Division of Mechanics of Solid Materials, Luleå University of Technology, 971 87 Luleå, Sweden

Abstract. Driven by current safety and weight reduction policies in the automotive sector, the development of new high strength sheet metal products has experienced unprecedented growth in the last years. With the emergence of these high strength materials, new challenges related to their limited ductility and higher cracking susceptibility have also raised. Accordingly, the development of new fracture criteria accounting for the material's cracking resistance has become unavoidable. In this work, a new cracking resistance index (CRI) based on fracture mechanics is proposed to classify the crack propagation resistance (i.e. the fracture toughness) of high strength metal sheets. The index is based on the fracture energy obtained from tensile tests with sharp-notched specimens. The procedure is very fast and simple, comparable to a conventional tensile test, and it may be used as routine testing for quality control and material selection. The *CRI* is investigated for several advanced high strength steel (AHSS) sheets of 0.8-1.6 mm thickness with tensile strengths between 800 and 1800 MPa. The results show that the proposed index is suitable to rank high strength steel sheets according to their crack propagation resistance and it can be correlated to the material's crashworthiness and edge cracking resistance.

1. Introduction

The automotive industry is continuously facing new challenges to satisfy the increasingly stringent safety and CO_2 emission legislations. In this sense, large research efforts have been put on material innovation in order to develop lighter and safer vehicle structures. Advanced high strength steels (AHSS) are one of the key materials in this vehicle lightweighting process. Their enhanced mechanical properties combining high strength and good formability, together with the relatively reduced production costs compared to other high-performance materials, are some of the main factors that have fostered their widespread implementation in autobody structures [1].

However, increasing strength usually comes at the expenses of ductility. Consequently, the implementation of these high strength materials has also brought new issues related to their higher cracking susceptibility during forming [2-4] or under impact loading [5-7]. The development of steel grades with higher strength levels, and thus higher cracking sensitivity, increases the frequency of this type of failures, which can limit the applicability of some AHSS grades and become a real problem to stampers and automotive product developers. With all this in mind, it is evident that there is an increasing need to know the fracture properties of AHSS to understand their cracking behaviour during cold forming or in-service.

Previous works by the authors have shown that fracture toughness, in particular the essential work of fracture (EWF), may be a suitable property to understand the cracking resistance of AHSS and predict edge cracking resistance [3, 8-10] and crash performance [7]. On this basis, a new classification map based on the uniform elongation (*UE*) from uniaxial tensile tests and the specific essential work of fracture (w_e) was proposed in [10] to provide a more comprehensive description of AHSS formability and fracture resistance.

All these studies show that the EWF methodology [11] is a powerful tool to assess the crack propagation resistance of AHSS sheets and simpler than other fracture mechanics standard procedures. However, there is still some reticence in the implementation of these fracture mechanics techniques at the industrial level, mainly related to the complexity and elevated costs of specimen preparation. As recommended by fracture mechanics standard procedures [12, 13], to obtain representative and notch-independent fracture toughness values, it is required the nucleation and propagation of fatigue pre-cracks in the specimens to be tested [14]. These fatigue pre-cracking procedures are expensive and very time-consuming, which hinders making the leap from the laboratory to the industrial plant. In order to reduce the time for specimen preparation and facilitate the lab-to-industry transfer, a new rapid notching procedure was presented in [15]. The procedure was validated in different AHSS grades and showed to drastically reduce the time for EWF testing, providing equivalent results to fatigue pre-cracked specimens.

In the present work, the new rapid procedure has been used to evaluate the EWF of four cold-rolled AHSS grades with tensile strengths ranging from 1000 to 1800 MPa. Furthermore, a new cracking resistance index (CRI) is proposed to rank the crack propagation resistance of AHSS sheets. The index is based on the fracture energy of Double Edge Notched Tension (DENT) specimens but, contrary to EWF tests, a single specimen is required. The CRI is evaluated for a wide range of AHSS grades and it is compared to EWF results to verify its usefulness as a material ranking index.

2. Materials and methods

2.1. Materials

Four cold-rolled AHSS grades with thicknesses between 0.8 and 1.6 mm thickness are characterized in the present study. The investigated steel grades are a dual-phase steel (DP1000 A), two complex phase steels (CP1000HD and CP1180) and a press-hardened steel (PHS1800). The mechanical properties of these steels are shown in Table 1.

In addition, for the investigations on the CRI, a wide assortment of AHSS grades with a similar thickness (1.2-1.6 mm) studied in previous publications have been included. The range of steel grades analysed includes a Transformation Induced Plasticity (TRIP) steel, several DP and CP steels, two TRIP-aided bainitic ferritic (TBF) steels, two Quenching & Partitioning (Q&P) steels, a mixed TBF/Q&P steel and a Press Hardened Steel (PHS). This material selection ensures that the proposed methodologies apply to a broad variety of microstructures and mechanical properties. The main mechanical properties of all the steel grades used for analysis are given in Table 1. For more information, please refer to the publications indicated in the table. Note that the name of some of the steel grades might have changed.

Table 1. Mechanical properties of the investigated materials for the transverse direction. *t*= thickness, *YS*=yield stress, *UTS*= ultimate tensile strength, *UE*= Uniform elongation, *TE*= Total elongation at fracture.

Reference	Steel	t [mm]	YS [MPa]	UTS [MPa]	UE [-]	TE [-]
Present study	DP1000 A	0.8	735	1074	0.08	0.11
	CP1000HD	1.5	909	1062	0.07	0.11
	CP1180	1.5	1079	1215	0.05	0.08
	PHS1800	1.2	1499	1800	0.05	0.06
[10]	TRIP800	1.6	542	851	0.21	0.26
[10]	DP800HD	1.5	513	823	0.14	0.20
[16]	DP1000 B	1.4	773	1020	0.06	0.10
[7,14]	DP1000 C	1.4	775	1015	0.07	0.11
[3]	DP1000 D	1.2	697	1067	0.09	0.12
[16]	DP1000 E	1.4	816	1055	0.07	0.10
[7,14]	CP1000 A	1.4	915	1008	0.05	0.09
[3]	CP1000 B	1.2	904	986	0.06	0.08
[7,14]	TBF1000	1.5	755	1012	0.11	0.16
[7]	TBF/Q&P1000	1.4	876	1026	0.08	0.11
[7]	PHS1000	1.5	988	1007	0.05	0.07
[10]	DP1180HD	1.2	895	1212	0.08	0.14
[7,14]	Q&P1180 A	1.4	920	1202	0.05	0.09
[10]	Q&P1180 B	1.5	1034	1184	0.09	0.13
[10]	TBF1180	1.4	987	1216	0.09	0.13

2.2. Experimental Method

EWF tests were performed with rectangular sharp-notched DENT specimens. The edge notches must have a very small root radius, i.e. they must be as sharp as cracks. Such notch conditions may be obtained by the tool described in [15]. This rapid notching procedure is used to readily prepare the specimens and assure reliable and robust results in fracture resistance tests. Figure 1 shows some images of the experimental setup and the obtained specimen geometry. The rectangles were cut at transverse orientation with respect to the rolling direction and the notches were oriented in the longitudinal direction (T-L specimens according to ASTM E399 [12]).

Ligament lengths (distance between notches, l_0 in Figure 2) from 8 to 18 mm were obtained and 2-3 specimens per ligament length were tested. In total, 8 to 15 specimens per material were tested depending on material availability. The experimental procedure for the determination of the EWF is represented schematically in Figure 2. The DENT specimens were tested up to fracture at a constant displacement rate of 1 mm/min and the load (P) versus the load-line displacement (u) was recorded. The load-line displacement was measured by means of a video extensometer using initial extensometer marks separated 50 mm.

For each specimen, the total work of fracture (W_f) was obtained by integration of the area under the load-displacement curve. Then, the specific work of fracture (w_f) was calculated according to:

$$w_f = \frac{1}{l_0 t_0} * W_f \tag{1}$$

where W_f is the total work of fracture, l_0 is the initial ligament length and t_0 is the initial sheet thickness.

The essential work of fracture (w_e) was determined by extrapolation to ligament zero of the w_f vs l_0 data (Figure 2). More detailed information about the EWF methodology and its theoretical foundations can be found in previous publications [7, 11, 14].
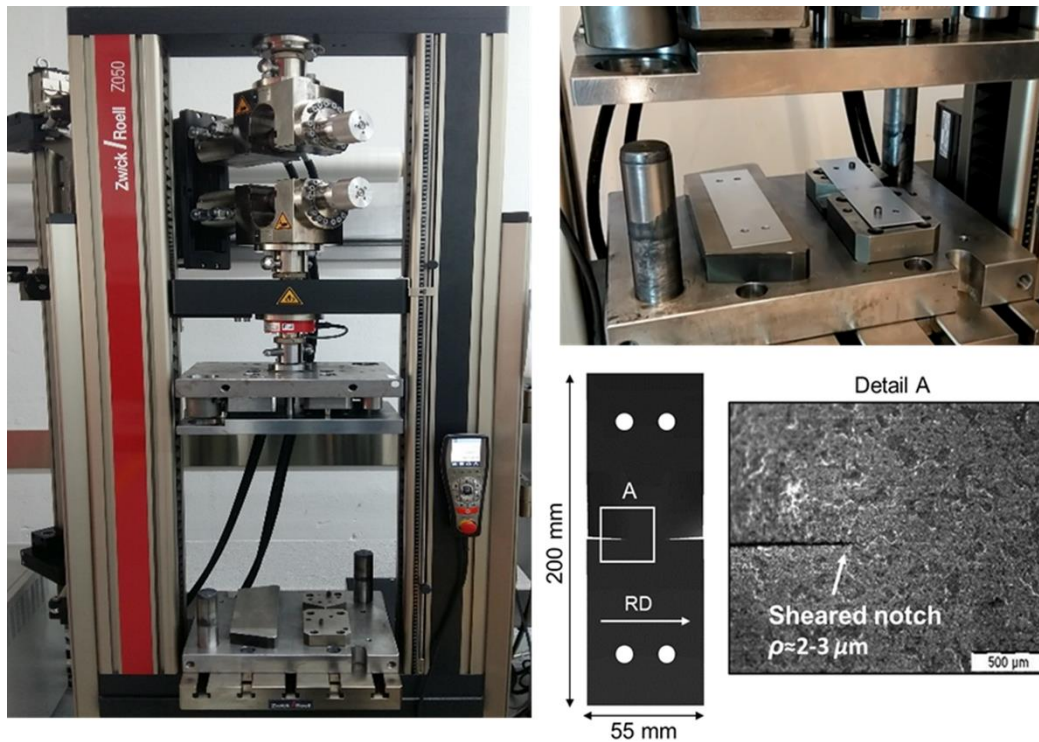

Figure 1. Experimental setup of the rapid notching procedure and obtained DENT specimen. Detail A shows a microscope image of the notch tip (notch radius, $\rho \approx$ 2-3 μm). RD: rolling direction.
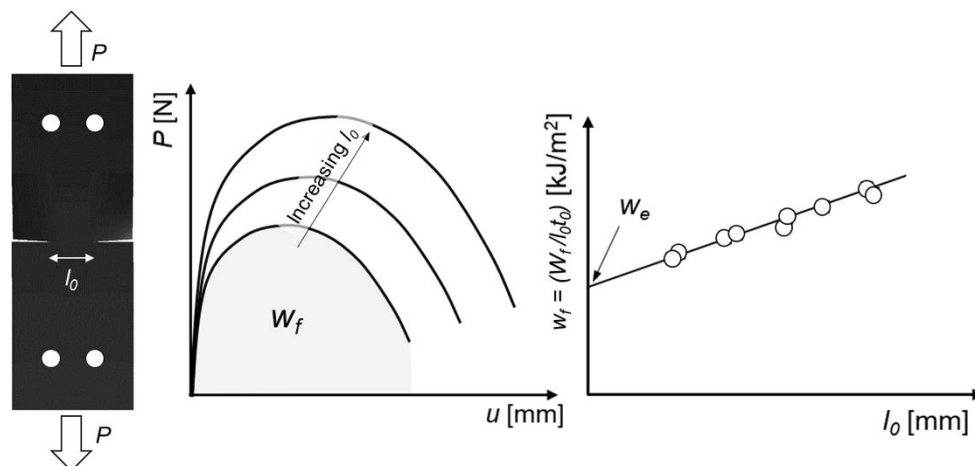

Figure 2. Experimental determination of the EWF: W_f for different ligament lengths (l_0) and plot of wf against l_0. The y-intercept indicates the specific essential work of fracture, w_e.

3. Results and discussion

3.1. EWF results

The results of EWF tests for the four AHSS grades are shown in Figure 3. The figure shows the values of w_f as a function of the ligament length. The specific essential work of fracture (w_e) is given by the y-intercept of the linear regression of w_f vs l_0 data.

The press-hardened steel grade PHS1800 shows the lowest crack propagation resistance of the investigated steels. Its essential work of fracture is far below the steel with greater fracture toughness, the CP1000HD. Comparing the two 1000 MPa steel grades, DP1000 A and CP1000HD, it can be observed that the CP grade shows significantly higher w_e than the DP one. This is in good agreement with the observations made in previous studies [3,7-9]. However, it is important to note that DP1000A shows a lower thickness (t= 0.8 mm). w_e has a significant contribution from necking and, thus, depend on specimen thickness [14,16]. Unfortunately, the influence of specimen thickness on w_e is material dependent and is not necessarily linear, making difficult the direct comparison with other steel grades. Therefore, only materials with similar thickness, such as CP1000HD and CP1180, should be compared. In this case, the steel CP1180 shows significantly lower fracture toughness than the CP1000HD and slightly lower than the published in [7] for a CP1200 with equivalent thickness.
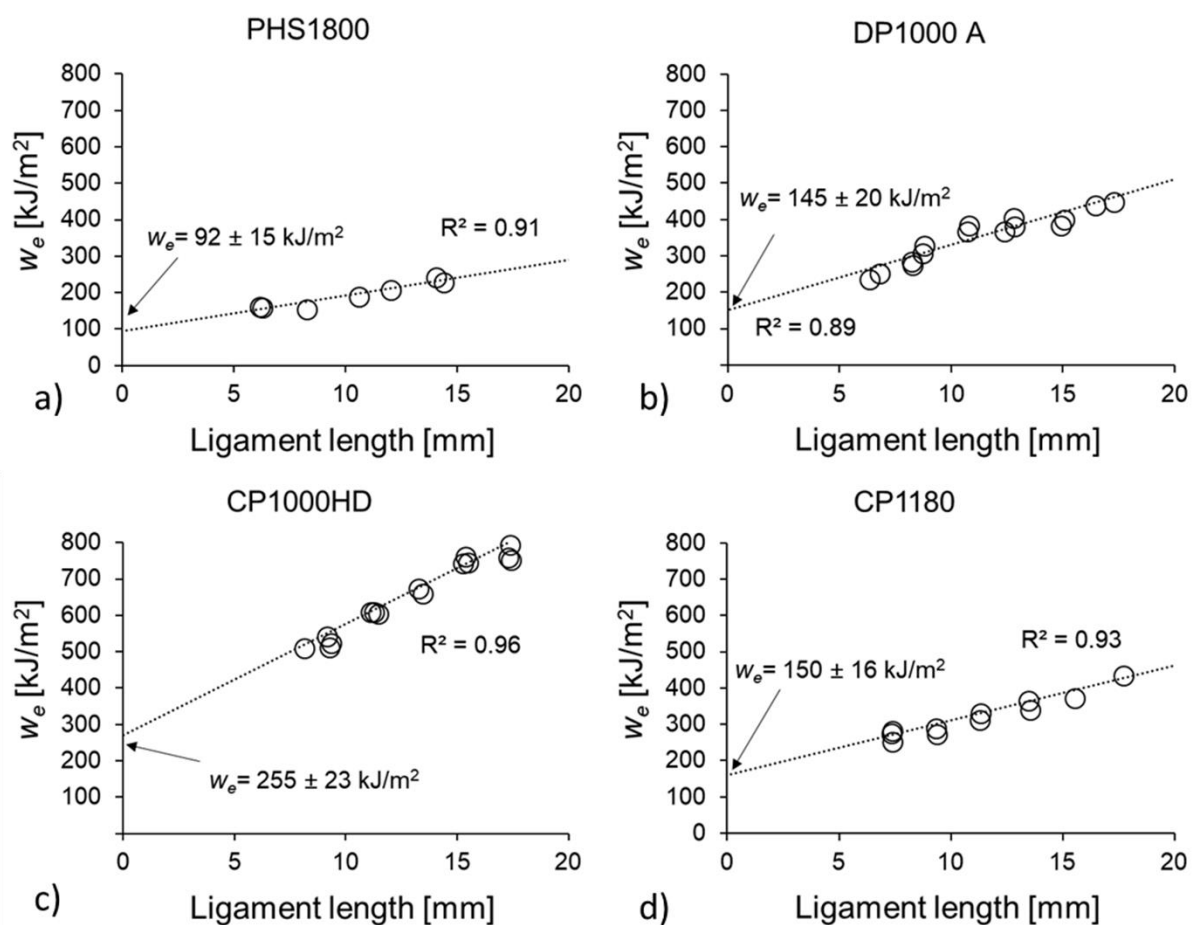

Figure 3. w_f as a function of the ligament length. w_e and the correlation coefficient R^2 are indicated.

3.2. Correlation between essential work of fracture and tensile properties

It has been traditionally assumed that materials with greater elongation or greater UTSxTE product have greater toughness. However, as discussed in various works [10, 14, 16], tensile properties are not suitable to estimate the cracking resistance of AHSS. The relationship between the specific essential work of fracture and uniaxial tensile parameters for all the AHSS grades shown in Table 1 is analysed in Figure 4. The figure shows once more that no direct link can be established between tensile properties and w_e.

Hence, parameters such as elongation or UTSxTE are not good indicators of the material's crack propagation resistance.
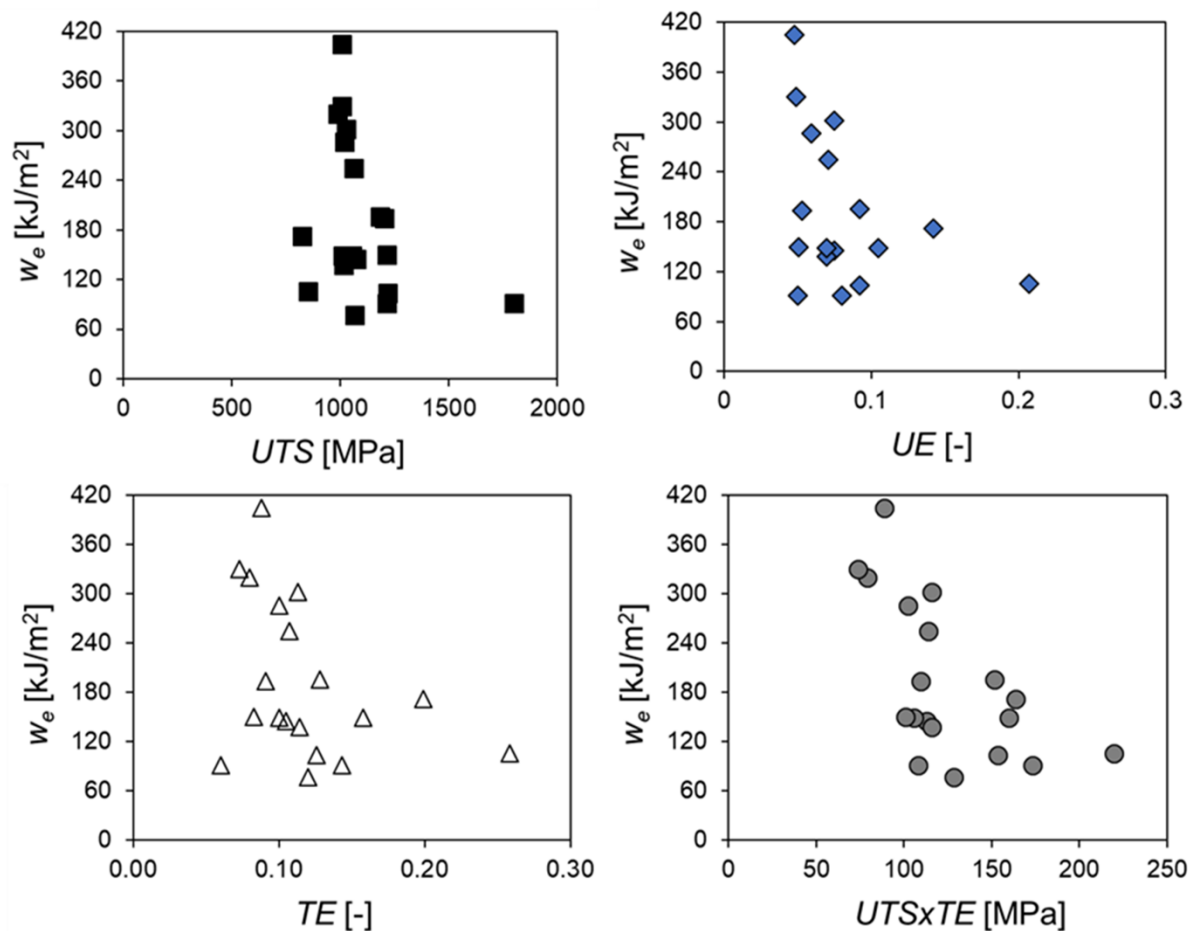

Figure 4. w_e as a function of tensile properties

3.3. Definition of a Cracking Resistance Index

In this section, a new Cracking Resistance Index (CRI) is proposed to estimate the fracture toughness of AHSS sheets. The objective is to provide an easy-to-measure parameter that allows ranking AHSS according to their crack propagation resistance.

EWF testing is a quite simple method to evaluate the fracture toughness of AHSS sheets and, with the rapid notching procedure, the tests can be performed in a few minutes. However, the methodology involves the preparation of multiple specimens with different ligament lengths which can make the procedure a bit slower and troublesome for in-plant material control purposes. The aim of testing different ligament lengths is to separate the energetic contribution of the essential work of fracture (w_e) developed in the fracture process zone from the plastic energy dissipated around the crack tip (βw_P). The first term is a thickness-dependent material constant that represents the *real* fracture toughness of the material while the second is a geometry-dependent factor associated with plasticity. Since in ductile fracture energy both terms are intermingled, in other single-specimen methods such as the Kahn-type tear tests this energy partitioning is not possible. Therefore, the obtained "toughness" values may be misleading and yield wrong material ranking [14,17].

The idea here is to use a single-specimen parameter, i.e. a single ligament length, that provides similar material ranking to EWF tests. For this purpose, first, the correlation between w_f for ligament lengths of 8 ($w_{f\,L8}$), 10 ($w_{f\,L10}$) and 13 mm ($w_{f\,L13}$) and w_e is investigated in Figure 5 a-c. The figure shows that the best correlation is obtained for the w_f with the smallest ligament length ($w_{f\,L8}$). As the ligament length increases, the correlation decreases. This is because the larger the ligament length the greater the contribution from the plastic work to the total fracture energy and, thus, the larger the difference with respect to the essential work of fracture. In this case, the smallest ligament length is limited to 7-8 mm since the minimum length that can be obtained with the mechanical notching tool is about 6.5 mm.

Nevertheless, the correlation of $w_{f\,L8}$ with w_e is not good enough to use it as a crack propagation resistance indicator since it is still containing an energetic contribution from plasticity. This extra contribution from plastic work may be associated with the material's strength and global ductility, which can be represented by the tensile strength and elongation, respectively. In other words, materials with lower strength and greater elongation have a larger contribution from the plastic work dissipated out of the fracture process zone.

According to this, a CRI based on the total work of fracture of DENT specimens and accounting for the contribution of global ductility to fracture energy was defined as follows:

$$CRI\ [\%] = \frac{W_{fL8}}{UTS \cdot TE \cdot t_0 \cdot l_0^2}\ x\ 100 \tag{2}$$

where W_{fL8} is the energy under the load-displacement curve of a DENT specimen with ligament length ≈8 mm, UTS is the ultimate tensile strength, TE is the total elongation, t_0 is the sheet thickness and l_0 is the ligament length. The CRI is expressed as a percentage. The calculated CRI values for all the investigated AHSS grades are given in Table 2, together with the data used for calculation and the w_e. Note that the CRI has been calculated with the fracture energy of only one DENT specimen for each material. It would be recommendable to test at least three replicates for improving statistical reliability.

Figure 5d shows that the correlation between the CRI and the essential work of fracture is significantly improved (R^2=0.96), which suggests that the CRI can be used as an indicator of the crack propagation resistance of AHSSs. To validate the material classification obtained by using the CRI, it is plotted together w_e in Figure 6. As observed in the figure, the CRI provides a very similar material ranking to the obtained by means of the EWF methodology, thus corroborating its validity as a crack propagation resistance indicator. On the other hand, the use of this index also allows defining different cracking resistance levels for material classification, as illustrated in Figure 6:

- Low cracking resistance (CRI ≤ 25 %)
- Medium cracking resistance (25% < CRI ≤ 50%)
- High cracking resistance (CRI > 50%)

Based on these results, the proposed CRI is posed as a useful parameter for material classification and fracture performance estimation of AHSS. It must be emphasized that the CRI should be only used as a first approximation for fast material screening and, in any case, should replace the proper fracture toughness evaluation of AHSS sheets in the frame of fracture mechanics.
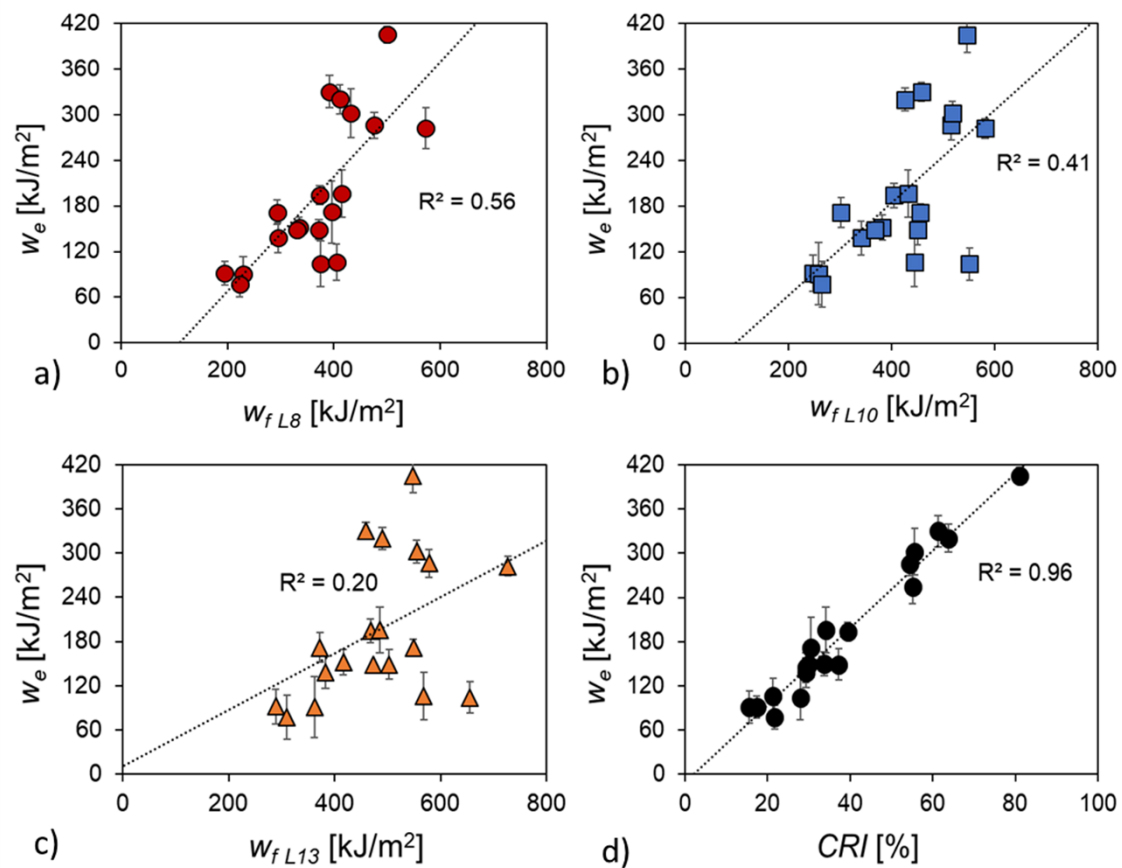
Figure 5. Correlation between w_e and a) $w_{f\,L8}$, b) $w_{f\,L10}$, c) $w_{f\,L13}$ and d) CRI. The error bars indicate the standard deviation of w_e.

Table 2. Data used for calculation of the CRI. w_e and HER are also indicated.

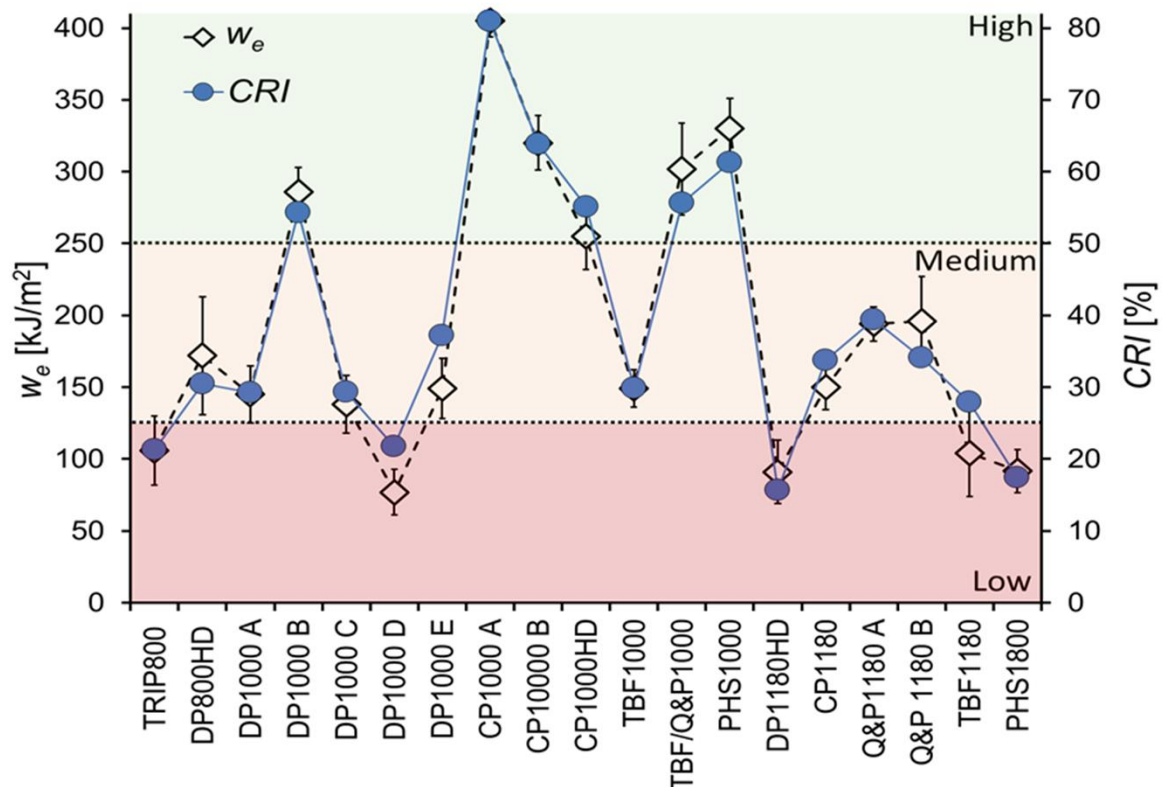| Steel	t [mm]	w_e [kJ/m²]	UTSxTE [MPa]	W_{fL8} [Nmm]	Actual ligament length, l_0 [mm]	CRI [%]	HER [%]
DP1000 A	0.8	145 ± 20	113	2224	8.3	29	27 ± 2
CP1000HD	1.5	255 ± 23	114	7220	8.4	55	70 ± 3
CP1180	1.5	150 ± 16	101	2779	7.4	34	65 ± 5
PHS1800	1.2	92 ± 15	108	1535	8.3	17	-
TRIP800	1.6	106 ± 24	220	5607	8.6	21	23 ± 3
DP800HD	1.5	172 ± 41	164	4648	7.9	31	34 ± 3
DP1000 B	1.4	286 ± 17	102	5719	8.6	54	-
DP1000 C	1.4	138 ± 20	116	3593	8.7	29	35 ± 7
DP1000 D	1.2	77 ± 16	128	2141	8.0	22	17 ± 5
DP1000 E	1.4	149 ± 21	106	3742	8.4	37	38 ± 1
CP1000 A	1.4	405 ± 11	89	4878	7.0	81	85 ± 4
CP1000 B	1.2	320 ± 19	79	4027	8.2	64	59 ± 13
TBF1000	1.5	149 ± 13	160	4355	7.8	30	30 ± 1
TBF/Q&P1000	1.4	302 ± 32	116	4052	6.7	56	66 ± 11
PHS1000	1.5	330 ± 21	74	5116	8.7	61	57 ± 1
DP1180HD	1.2	91 ± 22	173	2319	8.5	16	32 ± 1
Q&P1180 A	1.4	194 ± 12	109	4495	8.7	39	55 ± 8
Q&P1180 B	1.5	196 ± 31	152	4999	8.0	34	41 ± 4
TBF1180	1.4	104 ± 30	153	3860	8.1	28	28 ± 2

Figure 6. Comparison of w_e and CRI. The error bars indicate the standard deviation of w_e. Three cracking resistance levels are defined according to the CRI.

3.4. Application of the CRI for cracking behaviour prediction

The use of the specific essential work of fracture to predict the cracking performance of AHSS has been discussed in several works [3, 7-10, 14, 17]. Based on the very good correlation established between w_e and Hole Expansion Ratio (HER) measured according to ISO 16630, the EWF is considered as a useful material property to predict edge cracking resistance [3,8-10]. The EWF methodology was also used in [7] to investigate the cracking behaviour of several AHSS grades during axial impact loading tests. The results showed that steels with higher w_e also presented a lower degree of cracking during the impact and, in general, a better crash performance. According to this, the EWF has become an important material parameter to take into consideration in material design and selection.

As shown in the previous section, the CRI proposed in this work is a good indicator of the material's fracture toughness and correlates very well with w_e. Therefore, it should be also useful to predict the cracking behaviour of AHSS during cold forming or in a crash situation. The correlation between the CRI and the HER for the AHSS grades investigated in this work is investigated in Figure 7. The HER for three of the four AHSS characterized in this work has been evaluated according to ISO 16630. HER results for the other steel grades are extracted from literature [3, 8, 10]. HER values are given in Table 2. Figure 7 shows a quite good correlation between the CRI and the HER, which confirms the suitability of the index for edge cracking resistance prediction.
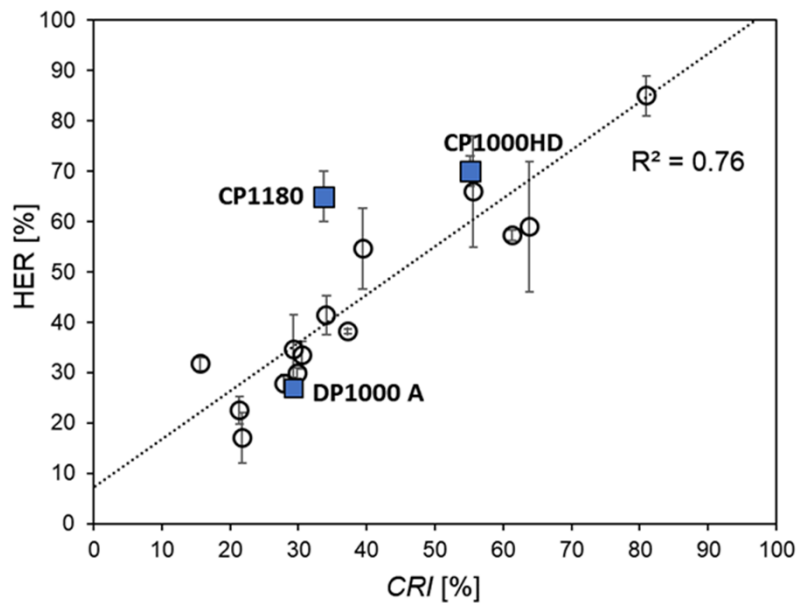
Figure 7. Correlation between CRI and HER for different AHSS grades. Materials characterized in the present study (in blue) together with results from literature (open symbols) [3,8,10]. The error bars indicate the standard deviation of HER.

4. Conclusions

In the present work, a rapid notching procedure has been used to evaluate the fracture toughness of four AHSS sheets by means of the EWF methodology. The method is intended to introduce very sharp crack-like sharp notches in rectangular thin sheet metal specimens through a mechanical shearing process. The results presented in this work have shown that, with the studied cutting conditions (sharp punch, cutting clearance ≈ 5-10%), the method is an effective solution to evaluate the crack propagation resistance of AHSS in a simple and fast manner. The influence of cutting parameters such as punch wear or cutting clearance on the results (notch geometry, deformation caused by shearing, fracture energy, etc.) is currently under study. However, it must be noted that the aim of the proposed procedure is not to reproduce the trimming process in production but to obtain notches with the sharpest possible tip, resembling that of a crack. Therefore, the cutting parameters should be optimized to improve the notch tip quality and minimizing the deformation in the uncracked ligament area.

On the other hand, a new Cracking Resistance Index (CRI) has been proposed for AHSS classification. The CRI has shown to be useful to predict the crack propagation resistance of AHSS sheets and it can be used as a fracture toughness indicator for material ranking. The index shows a good correlation with ISO 16630 HER, which allows using it as a parameter for edge cracking resistance estimation. The proposed CRI must be used only as a fracture toughness index for material screening.

The combination of the rapid notching procedure and the use of the CRI offers a fast and cost-effective method to estimate the crack propagation resistance of AHSS. The methodology might be implemented as a routine procedure for in-plant quality control and material selection and/or acceptance.

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