Toughness evaluation of high strength steels sheets by means of the essential work of fracture

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Abstract. Advanced high strength steels (AHSS) are increasingly being applied in safety related automotive components. Thus, a detailed knowledge of their fracture properties, as fracture toughness, is needed to properly design high performance components. Fracture toughness (K_{IC}) cannot be readily measured in metal sheet. It is because the small thickness (1-3 mm) is not enough to develop a plane strain state, requirement that must be met to properly calculate K_{IC}, as states the ASTM E399 procedure. In this sense the essential work of fracture (EWF) has been successfully applied to determine fracture toughness in polymers films and some metal sheets as aluminum alloys, low Carbon steels, stainless steels, brass, etc. However, there is no enough information about the applicability of this methodology to AHSS, due to the assumption that the ligament area must be fully yielded before the onset of crack propagation. In these terms, optical 3D deformation analysis allows to measure the strain on the ligament area during sample loading and to calculate the yielded area. In the present work the fracture toughness of some advanced high strength steel sheets has been measured by means of the EWF. The results show that AHSS sheets can meet the requirements of the method, and therefore the values obtained for the EWF are valid. Thus, the EWF is postulated as methodology to evaluate the fracture toughness and can be used as a mechanical parameter to characterize the crash behavior of AHSS steel sheets.

Introduction

Advanced high strength steels (AHSS) are increasingly being applied in safety related automotive components taking advantage of their high mechanical properties. AHSS allows lightweight construction by reducing the component cross section in comparison to conventional steels. Moreover, AHSS present high energy absorption during crash test, which allows producing components with high crashworthiness. Structural components such as B-pillars, longitudinal beams, bumper reinforcements among others are currently being manufactured with different grades of AHSS.

Automotive industry is continuously looking for strategies for further weight reduction. The thickness of structural components can still be reduced if the fracture behavior during crash is optimized. In this sense fracture toughness would be a useful property to take into account when evaluating crashworthiness of metal sheets for structural parts. However, fracture toughness cannot be readily measured in metal sheets because its limited thickness (1-3 mm) does not allow developing a plain strain state in front of the crack tip. The essential work of fracture (EWF) can be used to overcome such problem. This method has been successfully applied to determine fracture toughness in polymers films and many metal sheets.

The EWF is experimentally evaluated by following the methodology developed by Cotterell and Reddel [1]. They proposed that the total work of fracture (W_f) during the ductile fracture of a double edge notch specimen (*DENT*, Fig. 1) can be separated into two components: i) The essential work of fracture (w_e) spent in the *fracture process zone* (*FPZ*), and ii) non-essential plastic work (w_p) dissipated in an *outer region.*

$$W_f = w_e lt + w_p \beta l^2 \quad (1)$$

β is a shape factor that depends on the shape of the plastic zone, t is the sheet thickness and l is the ligament length between the two notches. The specific work of fracture w_f is obtained by dividing equation (1) by the initial ligament area (lt). It can thus express as:

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

If the w_f is plotted against the ligament length l, a straight line with a positive intercept, which is the specific essential work of fracture, is obtained. However, there are some restrictions that must be met in order to use equation (2): the ligament area must be completely yielded before crack initiation and the ligament must be in a plane stress state [1]. To accomplish those restrictions, the lower ligament length should be 3 to 5 times the thickness of the sheet, ($3t< l_{min} < 5t$) (1). The upper limit should not be larger than the 1/3 times the width of the specimen (W/3) or 2 times the radius of the plastic zone in plane stress at the crack tip r_p [2, 3].

$$r_p = \frac{1}{2\pi}\left(\frac{K}{\sigma_y}\right), \quad (3)$$

where K is the applied stress intensity factor and σ_y is the yield strength of the material. EWF can be considered a measure of the crack propagation resistance in the steady-state conditions, as the critical J-Integral at crack initiation, J_c [4]. EWF test has become very popular particularly in the evaluation of the toughness of thin polymer sheets [5], [6]. It has also been used to characterize different metal sheets as zinc alloys [2], aluminum alloys [7], bronze and brass [4], TRIP steel [8], and low alloyed steels [1, 3].

When applying the EWF methodology to metal sheets it should be kept in mind that the obtained values of w_e are greatly affected by the notch root radius. Such effect has been experimentally demonstrated in a mild steel [9] and in a metal composite [10]. The effect of the notch root radius on the fracture toughness measurement is well known in plain strain fracture toughness tests, below a critical notch root radius value the fracture toughness measurements are independent of the notch radius and are considered as a material intrinsic property. To avoid the effect of notch root radius, the ASTM procedure for evaluating the fracture toughness in suggests the nucleation of a fatigue crack at the notch root. This fatigue crack has the lowest possible radius at the crack tip, ensuring valid fracture toughness values. Similarly, in the EWF methodology, notches with the lowest possible root radius must be used. Again, fatigue cracks propagated through the notch should be the best option.

Only few works are devoted to the effect of notch root radius on the values of w_e for AHSS. Thus, if the essential work of fracture is considered to be a design parameter for crash resistance components, the values of w_e should be properly measured. Accordingly, the aim of the present work is to characterize the fracture toughness of two AHSS steel grades, a Dual Phase Steel (DP780 and DP1000) by means of the EWF method, assessing its applicability and testing the sensitivity of the methodology to the notch root radius. The fracture toughness of a low Carbon steel, DC03, was also measured for comparison purposes.

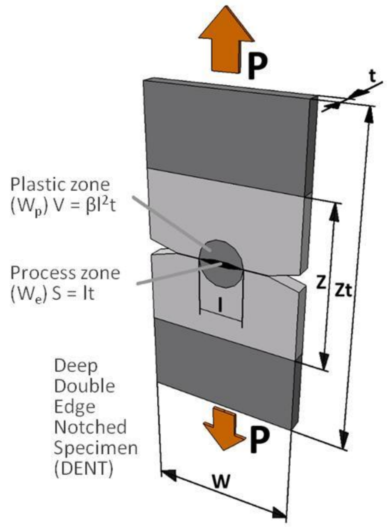


Fig.1. Double edge-notched sample (DENT).

Materials

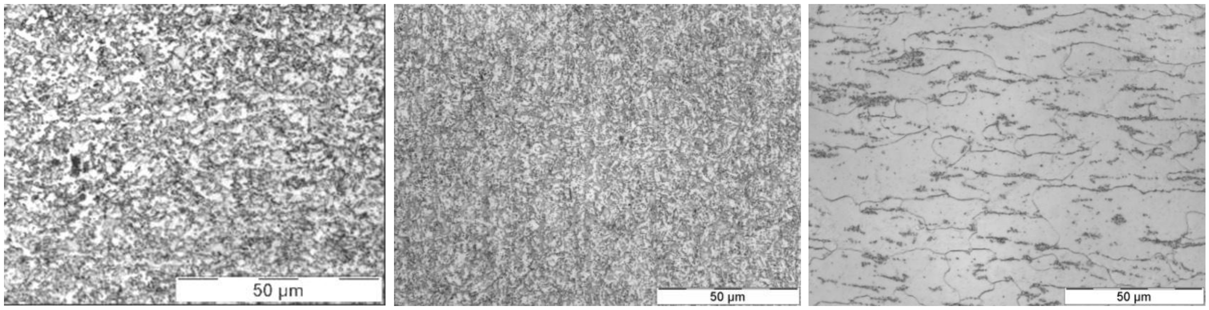
The materials used in this investigation were two Dual Phase Steels, DP780 and DP1000 with thicknesses 1.5 and 2.0 mm respectively; and a drawing quality steel DC03 with a thickness of 1.5mm. The tensile properties and the chemical composition were summarized in Table 1.

Table 1. Mechanical properties of the investigated steels and main alloy elements.

Steel	Yield Stress [MPa]	Ultimate Tensile Strength [MPa]	*n*	Elongation [%]	Chemical composition [% weight]				
					C	Si	Mn	Al	Cr
DC03	186	314	0.206	40	0.08	0.01	0.29	0.04	0.51
DP780	559	819	0.161	24	0.13	0.21	1.89	0.03	0.18
DP1000	798	1059	0.140	11	0.17	0.21	1.59	0.05	0.05

The microstructures were revealed by etching with Nital 2%, Fig. 2. The Dual Phase steels show martensitic matrix with ferrite in grain boundaries. Meanwhile, the microstructure of DC03 steel shows ferrite matrix (elongated in rolling direction) with black pearlite colonies.

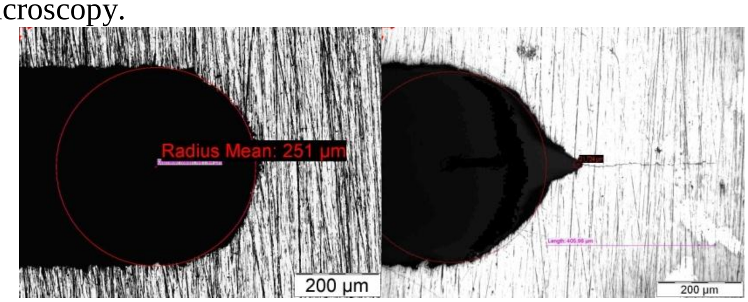
The DENT specimen, see Fig. 1, consists of rectangular plates with length of 240 mm transverse to the rolling direction, width of 55 mm and thickness (t) of 1.5 or 2.0 mm depending on the sheet.



(a) (b) (c)

Fig.2. Microstructure of steels. a) DP780 steel, b) DP1000 steel and c) DC03 steel.

Different notch root radius (ρ) were studied. The initial notch root radius (ρ) of specimens was 250µm, obtained by electrodischarge machining. The lowest possible value of ρ was obtained by nucleating a crack by fatigue from the notch root, Fig. 3. It is assumed to be the lowest possible radius, an a value of ρ about lower than 0.1µm was assumed after inspecting the the crack tip by scanning electron microscopy.



(a) (b)

Fig.3. Notch root radii (ρ) of DENT specimens a) 250 µm and b) 0.1µm.

Experimental Procedure

The total work of fracture (W_f) was measured by loading the DENT samples in a universal testing machine with a speed of 1 mm/min. The displacement was measured with a video extensometer with gauge length of 50 mm. DENT specimens with initial ligaments (l) ranging from 6 mm to 16 mm were tested up to fracture. The specific total work of fracture (w_f) was obtained by integrating each load-displacement curves and rating by the initial ligament area and thickness (lt).

The onset of crack propagation was detected by unloading the samples with the maximum ligament length (l_{max}) at different loading levels and inspecting by optical microscopy the crack tip. Additionally, optical 3D deformation analysis with Aramis software (Developed by GOM mbH) was carried out to measure the strain on the ligament area during sample loading. Aramis is a system based on two CCD cameras which monitor the deformation surface [11].

Results

Applicability of the EWF methodology. The EWF methodology imposes that crack tip must be fully yielded before a crack (nucleated from the notch root in samples with ρ=250 or the fatigue crack) starts to propagate. In Fig. 4, the crack tip at different stages of the load-displacement curve for DENT specimens can be seen. Crack progressively blunts as load increases and at the maximum load a large plastic zone is observed.

To define when the onset of plastic deformation starts, it has used the true stress-strain representation in logarithmic coordinates, Fig. 5. According to Hollomon hardening law, σ=$K\varepsilon^n$, there are three zones o regions. The first one is the elastic region, followed by a region of transition between elastic and fully plastic behavior and finally, the material in last or third region is fully plastic [12]. In order to assess if the ligament area was fully yielded at the maximum load, strain in the center of the ligament area at the beginning of the third region was considered. As can seen in Fig. 5 for the DP1000 steel this value is 0.005 measured in Mises strain or effective strain, which corresponds to the plastic regime evaluated in unixial tensile tests Additionally, optical 3D deformation analysis performed on DP780 and DP1000 showed that at the maximum load in samples with l=l_{max}, the ligament area was fully yielded, as can be shown in Fig, 6 and 7.

All these experimental observations indicate that the condition of total yielding is fulfilled in the studied steels and the obtained values of w_e can be considered as valid.

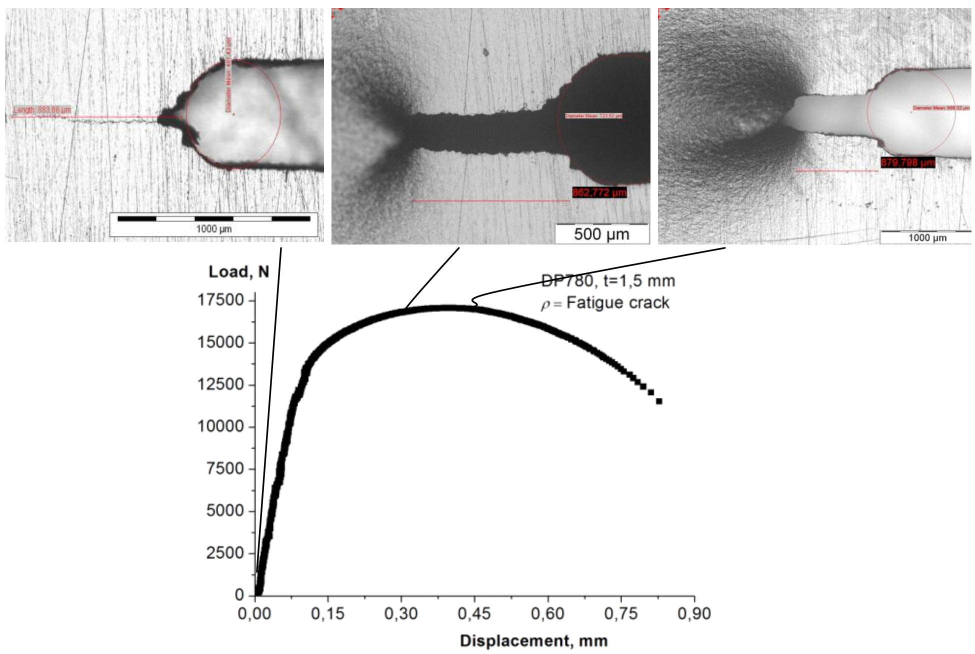


Fig. 4. Blunting at the crack tip at different stages of the test for DP780 with fatigue pre-crack. Tested samples have the maximum ligament length.

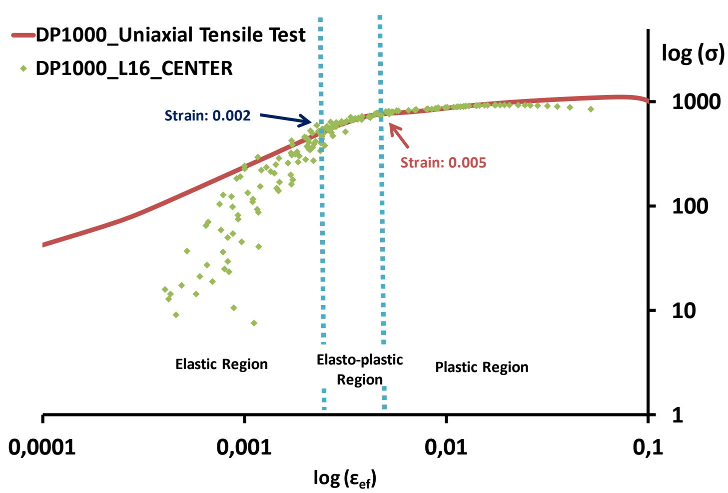


Fig. 5. True stress-strain curve in logarithmic coordinates for DP1000 steel at the center of the ligament (green data) and from a tensile test specimen (red curve).

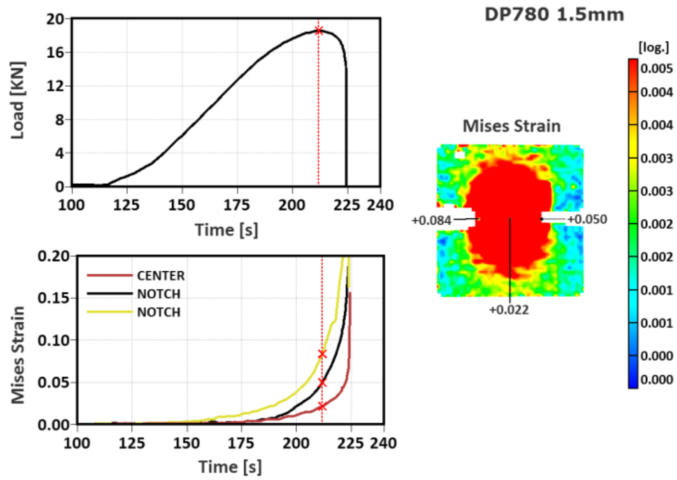


Fig. 6. Strain analysis in DP780 with fatigue pre-crack during fracture test. At P_{max} ligament area is fully yielded.

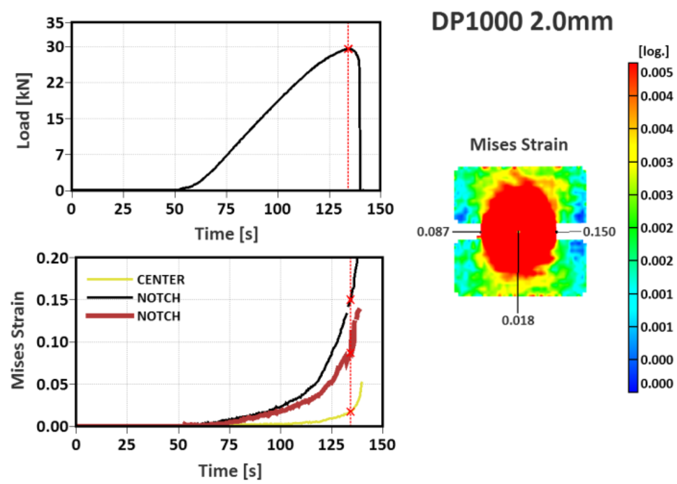


Fig. 7. Strain analysis in DP1000 with fatigue pre-crack during fracture test. At P_{max} ligament area is fully yielded.

Essential work of fracture. Fig. 8 and 9 show the values of w_f at different ligament size (l). The obtained values of w_e and specific non-essential work of fracture are summarized in Table 2.

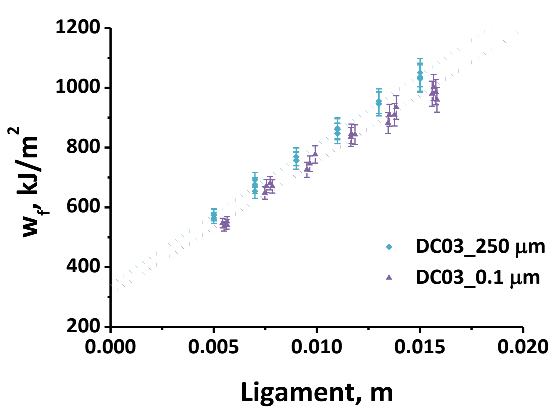


Figure 8. Linear regressions of the w_f vs l for DC03 for different values of the notch root radius (ρ).

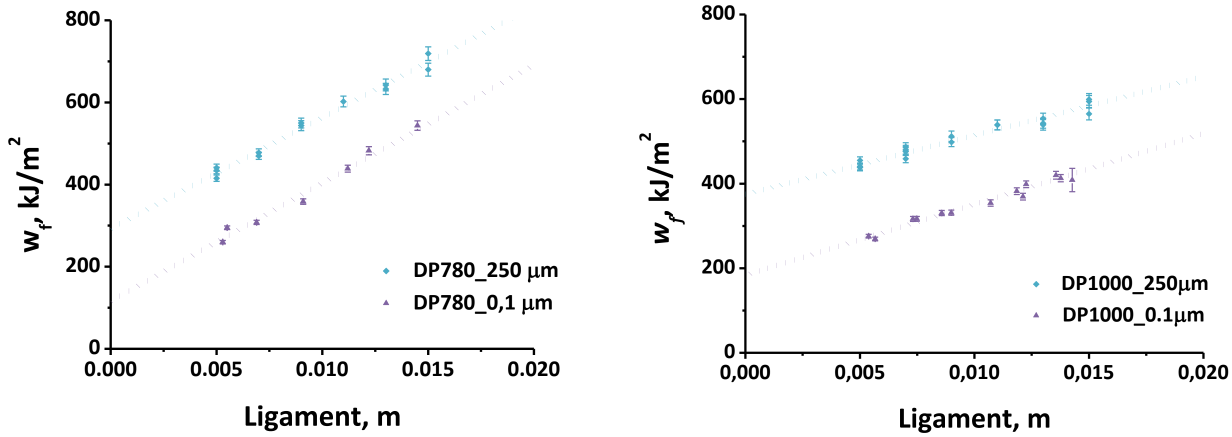


Figure 9. Linear regressions of the w_f vs l for DP780 and DP1000 for different values of the notch root radius (ρ).

Table 2. Essential work of fracture (w_e) for DP steels and DC03 steels.

Material	Thickness [mm]	Notch radii, ρ [μm]	w_e [kJ/m^2]	$w_{p\beta}$ [kJ/m^3]	R^2
DC03	1.5	250	342 ± 6	46681	0,996
DC03	1.5	0.1	309 ± 10	44303	0,98
DP780	1.5	250	293 ± 9	27061	0,98
DP780	1.5	0.1	116 ± 18	28754	0,96
DP1000	2.0	250	375 ± 7	16746	0.95
DP1000	2.0	0.1	184 ± 8	13906	0.97

Discussion

The validity of the EWF method is based on the assumption that the ligament area must be fully yielded before the onset of crack propagation. It has been experimentally probed for DP780 and DP1000 steels (Fig. 6 and 7), although the result for DC03 has not shown, as this steel shows a more pronounced plasticity, it would also accomplish with this requirement. Thus it can be stated that the EWF methodology can be applied to AHSS steels with a tensile strength up to 1000 MPa.

The calculated value for DC03, with ρ=250μm, is 342±5,7kJ/m^2, similar to those reported in literature for low Carbon steels. Knockaert and co-workers obtained a value of 400±15kJ/m^2 for a mild steel with thickness of 1.5mm and 225MPa of yield stress and ρ=200μm [13].

On the other hand, the obtained results of w_e for AHSS (DP780 and DP1000 steels), with different notch root radius, clearly show the dependence of w_e with respect to the notch root radii. The DC03 steel does not show this great dependence in notch radii, the results differs only by 10%. In another low carbon steel with yield stress of 330MPa, similar to DC03 steel, a critical notch radii of 150μm was found in CTOD toughness test [14]. Such result is in agreement with to the low dependence with the notch root radius experimentally measured in the present work for DC03 steel.

DP780 shows higher hardening coefficient and elongation than DP1000 steel. Thus, it can be expected to have higher toughness. However, the values of w_e are higher for DP1000 than for DP780. In order to understand this results, it should be considered that that the essential work of fracture have two energetic contributions, one is the work spent in generate necking and the other is the work to separate and create new surfaces. The work spent in necking is mainly related to the values of elongation and hardening coefficient. Accordingly, the higher value of w_e, found in

DP1000, with lower elongation and n value, would mean that the toughness in AHSS mainly comes from the energy to create new surfaces, rather than the energy spent in necking.

Summary

Based on the experimental results of the essential work of fracture on Dual Phase steels (DP780 and DP1000) and DC03, the following conclusions can be drawn:

- The EWF method can be applied to AHSS steel (i.e. DP780 and DP1000 steels), and DC03 to determine the toughness.
- There is a great dependence of w_e value respect to notch radii in AHSS steels, while in DC03 steel this reliance is lesser or minimal.
- The TEF methodology is postulated as a good tool for evaluating the fracture toughness to be used as a parameter to characterize mechanical fracture of AHSS.

Acknowledgements

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