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Test method for the determination of a cracking resistance index for advanced high strength steel sheets

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European foreword

This CEN Workshop Agreement (CWA 18012:2023) 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 2023-05-17, the constitution of which was supported by CEN following the public call for participation made on 2022-08-03. However, this CEN Workshop Agreement does not necessarily include all relevant stakeholders.

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Introduction

The continuous development of new complex multiphase advanced high-strength steel (*AHSS*) grades for automotive applications has brought the need for alternative formability and fracture performance classification criteria. Owing to their complex microstructures, superior strength and limited ductility compared to conventional mild steels, *AHSS* are more susceptible to cracking during forming [1-3] or in situations of severe deformation such as in crash scenarios [4-7]. Considering that the main usage of these high-performance sheet materials is for structural and safety-related components, it is obvious that knowing their cracking sensitivity and damage tolerance is essential for their safe implementation in the industry.

Fracture toughness, measured in the frame of fracture mechanics, is the most appropriate property to assess the crack propagation resistance of engineering materials. However, the measurement of the plane stress fracture toughness of metallic sheets is not widely extended in many industrial sectors like the automotive, especially because of the complexity of the Elastic Plastic Fracture Mechanics (*EPFM*) standardized testing methods. Most of these techniques, such as the *J*-integral and Crack Tip Opening Displacement (CTOD) procedures described in ASTM E1820 or the determination of a Crack Tip Opening Angle (CTOA) as described in ASTM E2472, are complex, expensive and time-consuming.

In this context, alternative simpler and faster experimental approaches, such as the Essential Work of fracture (*EWF*) methodology [8] or the Kahn-type tear tests [9], have been developed in order to satisfy the growing need of knowing the fracture properties of thin metallic sheets. For instance, the *EWF* has been used in several research works to explain the edge fracture sensitivity and crash performance of *AHSS* and press hardened steels (PHS) [10-13], becoming a relevant property for new high strength sheet materials development and selection.

The present CWA describes a new single-specimen testing method for the determination of a cracking resistance index (CRI) able to classify the crack propagation resistance of high strength metal sheets. The index is derived from the fracture energy obtained from tensile tests with pre-cracked or sharply notched specimens. Based on the good correlation observed between the *CRI* and the *EWF*, the *CRI* is proposed as a useful parameter to estimate the cracking sensitivity of *AHSS* [14]. The procedure is fast and simple, comparable to a conventional tensile test, and it may be used as an additional routine test for quality control and/or material ranking purposes. The CRI criterion is derived from the EWF methodology with a simplified approach requiring less specimens to be tested and less post-processing work.

1 Scope

This CWA describes a single-specimen testing procedure for the evaluation of a cracking resistance index (CRI) for *AHSS* sheets with thicknesses between 0,5 mm and 3,0 mm.

NOTE 1 The test method provides an estimated measure of the fracture resistance of thin *AHSS* in the presence of a crack.

NOTE 2 The proposed *CRI* must be used only as a fracture toughness index for material screening.

NOTE 3 The suitability of the test to estimate the cracking sensitivity of *AHSS* has been evidenced in a previous work by establishing a good correlation between the *CRI*, the *EWF* and the Hole Expansion Ratio (*HER*) for a wide range of multiphase *AHSS* grades [14].

NOTE 4 It must be emphasized that the results of the test are greatly affected by the specimen thickness. Therefore, it is recommended the use of specimens with similar thicknesses for comparative purposes.

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.

CWA 17793:2021, *Test method for determination of the essential work of fracture of thin ductile metallic sheets*

ISO 6892-1, *Metallic materials — Tensile testing — Part 1: Method of test at room temperature*

3 Terms and definitions

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

ISO and IEC maintain terminology 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
total work of fracture
W_f
energy obtained from the integration of the area under the load-displacement curve for the complete fracture

3.2
specific work of fracture
w_f
total fracture energy per unit area

3.3
cracking resistance index
CRI
toughness index, expressed in percentage, obtained from the specific work of fracture of a *DENT* specimen

4 Symbols and abbreviations

4.1 Symbols

Symbol	Unit	Designation
A	%	Percentage elongation after fracture in a uniaxial tensile test
B_o	mm	Original specimen thickness
b_o	mm	Original uncracked ligament length
F	N	Applied force
F_{max}	N	Maximum force obtained from a fracture test
L_t	mm	Specimen length
L_e	mm	Extensometer length for load-line displacement measurement
ρ	mm	Notch root radius
q	mm	Load-line displacement
q_f	mm	Load-line displacement at fracture
$R_{p0,2}$	N/mm^2	0,2 % offset yield strength
R_m	N/mm^2	Ultimate tensile strength
W	mm	Specimen width
W_f	kJ	Total work of fracture
w_f	kJ/m^2	Specific work of fracture
w_e	kJ/m^2	Specific essential work of fracture

4.2 Abbreviations

AHSS	Advanced High Strength Steels
CRI	Cracking Resistance Index
DENT	Double edge notched tension
EDM	Electrical discharge machining
EPFM	Elastic Plastic Fracture Mechanics
EWF	Essential work of fracture
HER	Hole Expansion Ratio
PHS	Press hardened steel

5 Principle

The method for the determination of the *CRI* requires the test of a fatigue pre-cracked or sharply notched rectangular Double Edge Notched Tension (*DENT*) specimen that is loaded up to fracture in quasi-static loading conditions. The specimens must be fractured using any mechanical test machine capable of quasi-static loading at a crosshead speed of 2 mm/min or less.

6 Significance and use

The significance of this test method is similar to that of the notch tensile test described in ASTM E338 and the tear test described in ASTM B871.

The main use of the method is to define a crack propagation resistance index for *AHSS* sheets. It is not intended to provide an absolute measure of fracture toughness and must be used solely for comparative and ranking purposes. The method can be useful for the research and development of new multiphase *AHSS* microstructures, to detect the influence of processing parameters and composition on fracture resistance, as an additional quality control criterion for material acceptance, etc.

Since the nature of the test makes it more sensitive to local microstructure inhomogeneities like inclusion size and distribution, it can provide relevant information about the fracture behaviour of *AHSS* sheets with similar tensile properties during forming or in service.

The main result of the test is the *CRI*, which is derived from the fracture energy of a *DENT* specimen with a defined initial ligament length (distance between the two cracks). The fracture energy is determined by the integration of the area under the load-displacement curve of the test. Other relevant parameters, such as the maximum load or the displacement at fracture, can also be obtained.

7 Equipment

7.1 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.

Testing machine stiffness can influence the data recording during the test. Therefore, the use of a relatively stiff machine is recommended. A not-enough stiff testing machine can cause the abrupt fracture of the specimens once the crack has started to propagate, providing lower energy values than desired. If this behaviour is observed regularly, it could indicate that a stiffer testing system is needed. Furthermore, it is recommended that for consistency of data, the same testing machine is used for all tests that are intended for direct comparison and relative rating of a group of materials.

The requirements of the system for load-line displacement are given in 7.2. Test fixtures are described in 7.3.

7.2 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 because all the elastic deformation in the test fixtures is then included in the displacement measurement and contributes to the fracture energies measured.

7.3 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 the whole 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.

8 Test specimens

8.1 Specimen dimensions

The recommended geometry is the Double Edge Notched Tension (*DENT*). Figure 1 a) shows the characteristic dimensions of a *DENT* specimen for the determination of the *CRI* according to this test method.

A rectangle of width W = 55 mm and length L_t = 200 mm is cut from the test material. The external contour can be cut, machined or spark-eroded. Alternative dimensions can be used depending on material availability. The minimum recommended dimensions are W = 40 mm and L_t = 90 mm.

The distance L_t includes the extensometer length, L_e, for load-line displacement and the gripping area. The extensometer length L_e should be 25 mm or 50 mm. The gripping distance shall be 50 mm.

To avoid the influence of notch radius on the measured fracture energies, the use of fatigue pre-cracked specimens is recommended. Alternatively, specimens with sharp notches can be used. The radius of the sharp notch, ρ, should be lower than 10 µm. Figure 1 b) shows an example of acceptable types of notches. The distance between the two sharp notches or cracks, the original ligament length, b_o should be 8 ± 1 mm.

Recommendations for specimen pre-cracking and notching are given in CWA 17793:2021. Alternative procedures, such as notch sharpening by using a razor blade are also valid. It must be noted that the shear-notching procedure described in CWA 17793:2021 is especially suitable for high-strength steels with yield strength $R_{p0,2}$ > 700 N/mm^2, which are less sensitive to the plastic deformation induced during the notching process. Therefore, special care must be taken when applying the method to lower-strength steels since the amount of plasticity generated at the crack tip may affect the obtained energy values. With the aim of preventing the effect of the notch preparation method, it is recommended to use the same notch configuration for all tests that are intended for the comparison of a group of materials.

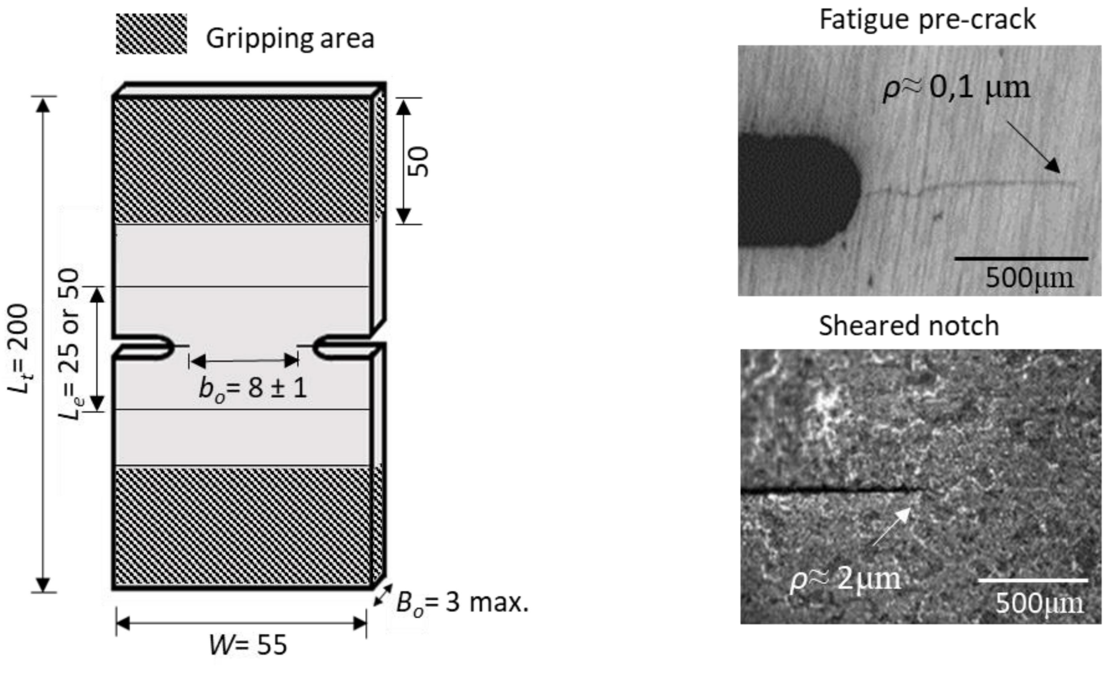


Figure 1 — a) dimensions of the *DENT* specimen geometry (in mm); b) examples of acceptable notches: fatigue pre-crack (upper row) and mechanically sheared notch prepared with the notching procedure described in CWA 17793:2021 (lower row)

8.2 Crack plane orientation

Orientation of the crack plane in relation to product geometry shall be decided before machining and identified according to the denomination defined in CWA 17793:2021.

9 Procedure

9.1 Pre-test measurements

The dimensions of specimens shall conform to those mentioned in 8.1. 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 first measured on 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 as described in 9.3.

9.2 Fracture test

The fracture tests shall be performed under displacement control at a constant displacement rate, sufficiently slow to ensure quasi-static conditions. Displacement rates between 0,5 and 2 mm/min are recommended. 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. The test should be stopped either when the load decreases by 40 % in a time frame of 100 ms or when it decreases to 20 N. Figure 2 shows the characteristic force versus load-line displacement curve obtained for a *DENT* specimen. In order to establish a reasonable estimate of average properties and improve statistical reliability, it is recommended to perform at least three replicates per testing condition.

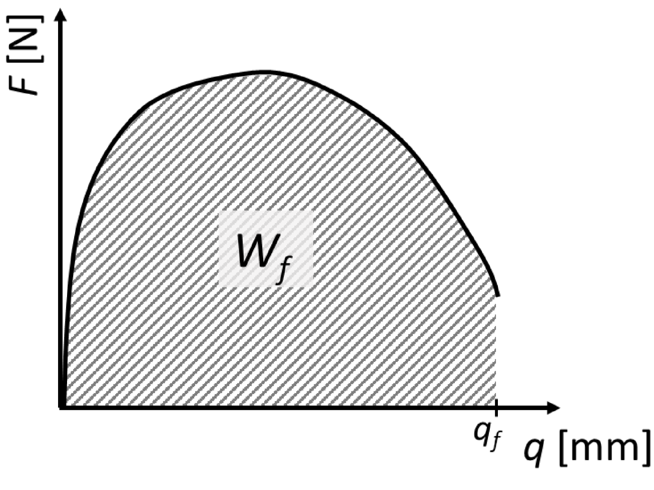


Figure 2 — Characteristic force (F)-displacement (q) curve obtained from the fracture test

9.3 Post-test measurements

After the test, the ligament length should be measured from the fracture surface of *DENT* specimens by using an optical microscope. At least five ligament length measurements shall be performed along the specimen thickness, as shown in Figure 3. The original ligament length, b_O, is determined from an average of the five measurements.

9.4 Calculations

Calculate the total work of fracture, W_f, by integration of the area under the load-displacement curve (Figure 2) and divide it by the initial cross-section area to obtain the specific work of fracture, w_f:

$$W_f = \frac{W_f}{b_o B_o} = \frac{1}{b_o B_o} \int_0^{q_f} F \cdot dq \qquad (1)$$

where

F is the force;

q is the load-line displacement;

q_f is the load-line displacement at fracture.

Then, calculate the cracking resistance index according to Equation (2):

$$CRI\,[\%] = \frac{w_f}{R_m \cdot \frac{A}{100} \cdot B_o \cdot b_o^2} \times 100 \qquad (2)$$

where

w_f is the specific work of fracture;

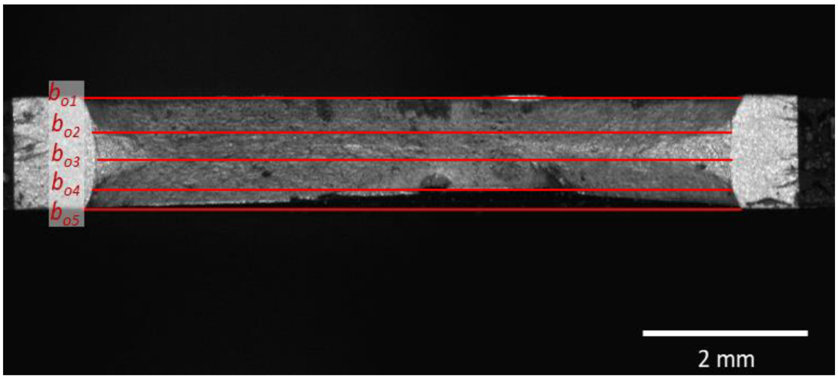
R_m is the ultimate tensile strength;

A is the percentage elongation at fracture from a uniaxial tensile test according to ISO 6892-1;

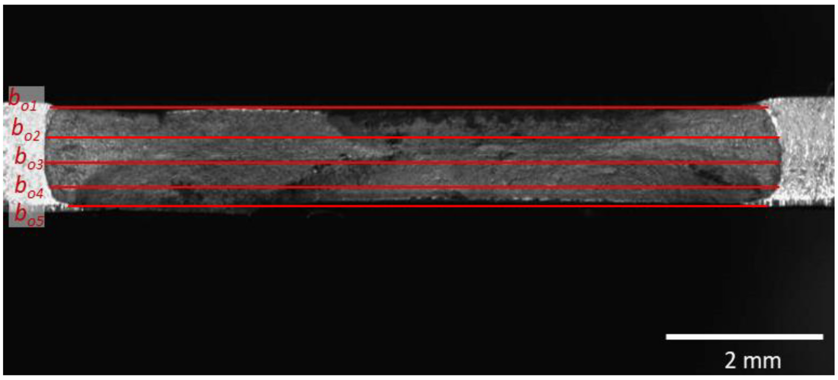
B_O is the specimen thickness;

b_O is the original ligament length;

The *CRI* is expressed as a percentage.



a)



b)

Figure 3 — Ligament length measurements on the fracture surface of *DENT* specimens for determination of b_o in a) fatigue pre-cracked specimen and b) shear notched specimen

10 Report

For each specimen, report the following information:

a) Material identification (steel designation, strength level).

b) Specimen number.

c) Specimen dimensions (W, L_t, L_e, b_o, B_o), in mm.

d) Test temperature, in degrees Celsius.

e) Test speed, in mm/min.

f) Specimen orientation.

g) Maximum load.

h) Displacement at fracture.

i) Specific work of fracture, w_f.

j) Cracking Resistance Index.

11 Application of the *CRI* to estimate the cracking sensitivity of *AHSS*

As evidenced in many research works, the *EWF* is a suitable parameter to rank the cracking performance of *AHSSs* during cold forming [11, 12] or in crash situations [10]. Therefore, it has become a relevant property for AHSS development and implementation.

Based on this premise, the ability of the *CRI* to estimate the cracking sensitivity of *AHSSs* was investigated in [14] by comparing it to the specific essential work of fracture (w_e) of different *AHSS* grades. The results are shown in Figure 4, where w_e is plotted as a function of the *CRI* for a wide range of multiphase *AHSS* grades with 0,8-1,6 mm thickness and tensile strengths between 800 and 1 800 N/mm^2. The figure shows a very good correlation between both terms, which indicates that the *CRI* can be used to estimate the crack propagation resistance of *AHSSs*.

Furthermore, a reasonably good correlation was also established in [14] between the *CRI* and the ISO 16630 [15] Hole Expansion Ration (*HER*), which is widely used in the industry as an edge cracking sensitivity parameter for metallic sheet materials. This trend suggests that the CRI is also a good indicator of edge fracture performance for AHSS, as already occurs with the EWF [11,12].

Although the HER is industrially accepted, its reliability is often questioned due to the large data scattering and the poor repeatability observed in several research works and round robin tests [16,17]. Moreover, it is not strictly a material parameter since it is affected by many experimental variables (hole preparation method, geometry of the expansion tool, crack detection method, etc.). On the contrary, the CRI can be considered an indicator of the material's fracture toughness, which may provide a more objective estimation of the cracking resistance of AHSS and help to better understand different crack-related phenomena, such as edge cracking or crash failure behaviour. These observations highlight the usefulness of the *CRI* as a cracking sensitivity indicator and support the implementation of this parameter for material screening as well as to define new material specifications for *AHSS* sheets.

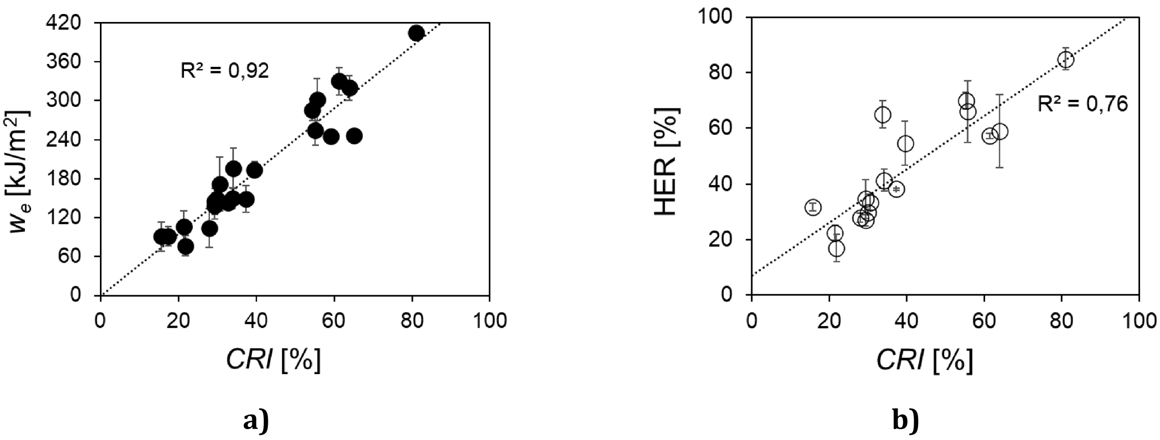


Figure 4 — Correlation between a) w_e and *CRI* and b) *HER* and *CRI* [14]

Bibliography

[1] Konieczny A., Henderson T. On Formability Limitations in Stamping Involving Sheared Edge Stretching. SAE Technical Paper 2007-01-0340, 2007

[2] K. Mori, Y. Abe, Y. Suzui. Improvement of stretch flangeability of ultra high strength steel sheet by smoothing of sheared edge. *J. Mater. Process. Tech.* 210 (2010) 653–659

[3] Silva C.R.M., Silva F.J.G., Gouveia R.M. Investigations on the edge crack defect in Dual Phase steel stamping process. Procedia Manuf. 2018, 17 pp. 737–745

[4] M.S. Walp MS. Impact Dependent Properties of Advanced and Ultra High Strength Steel. *SAE Technical Paper* 2007-01-0342, 2007

[5] Larour P., Pauli H., Kurz T., Hebseberger T. Influence of post uniform tensile and bending properties on the crash behaviour of AHSS and press-hardening steel grades. Proceedings of the IDDRG2010 (Graz, Austria) 2010

[6] Larour P., Naito J., Pichler A., Kurz T., Murakami T. Side impact crash behavior of press-hardened steels-correlation with mechanical properties. 5th Int. Conf. Hot sheet metal forming of high performance steel (CHS2) (Toronto, Canada, May 31- June 3 2015) pp 281-289

[7] Link T.M., Hance B.M. Axial and Bending Crash Performance of Advanced High-Strength Steels. Int. Symp. on New Developments in Advanced High-Strength Steels. Keystone, Colorado, USA. 2017

[8] Cotterell B., Reddell J.K. The Essential Work of Plane Stress Ductile Fracture. Int. J. Fract. 1977, ••• pp. 267–277

[9] Kaufman J.G., Knoll A.H. Kahn-Type Tear Tests and Crack Toughness of Aluminum Sheet. Metals Research and Standards, 1964, pp. 151–5.

[10] Frómeta D., Lara A., Molas S., Casellas D., Rehrl J., Suppan C. et al. On the correlation between fracture toughness and crash resistance of advanced high strength steels. Eng. Fract. Mech. 2019, 205 pp. 319–332

[11] Casellas D., Lara A., Frómeta D., Gutiérrez D., Molas S., Pérez Ll. et al. Fracture Toughness to Understand Stretch-Flangeability and Edge Cracking Resistance in AHSS. Metall. Mater. Trans., A Phys. Metall. Mater. Sci. 2017, 48 pp. 86–94

[12] Frómeta D., Lara A., Grifé L., Dieudonné T., Dietsch P., Rehrl J. et al. Fracture resistance of advanced high strength steel sheets for automotive applications. Metall. Mater. Trans., A Phys. Metall. Mater. Sci. 2021, 52 pp. 840–856

[13] Frómeta D., Parareda S., Lara A., Molas S., Casellas D., Jonsén P. et al. Identification of fracture toughness parameters to understand the fracture resistance of advanced high strength sheet steels. Eng. Fract. Mech. 2020, 229 p. 106949

[14] D. Frómeta, S. Parareda, A. Lara, L. Grifé, I. Tarhouni and D. Casellas A new cracking resistance index based on fracture mechanics for high strength sheet metal ranking 2021 IOP Conf. Ser.: Mater. Sci. Eng. 1157 012094

[15] ISO 16630:2017, *Metallic materials — Sheet and strip — Hole expanding test*

[16] Schneider M., Eggers U. 2011 Investigation on punched edge formability Proceedings of International Deep Drawing Research Group 2011 conference (Bilbao, Spain, June 5-8, 2014)

[17] Atzema E., Borsutzki M., Braun M., Brockmann S., Bülter M., Carlsson B. et al. 2012 A European round robin test for the hole expansion test according to ISO 16630 New Development in Sheet Metal Forming, Int. Conf. (Fellbach, Germany, May 23-24, 2012) pp 171-184

[18] ISO 9513, *Metallic materials — Calibration of extensometers used in uniaxial testing*

[19] ISO 7500-1, *Metallic materials — Verification of static uniaxial testing machines — Part 1: Tension/compression testing machines — Verification and calibration of the force-measuring system*

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

[21] ASTM E338, *Standard Test Method of Sharp-Notch Tension Testing of High-Strength Sheet Materials*

[22] ASTM B871, *Standard Test Method for Tear Testing of Aluminum Alloy Products*