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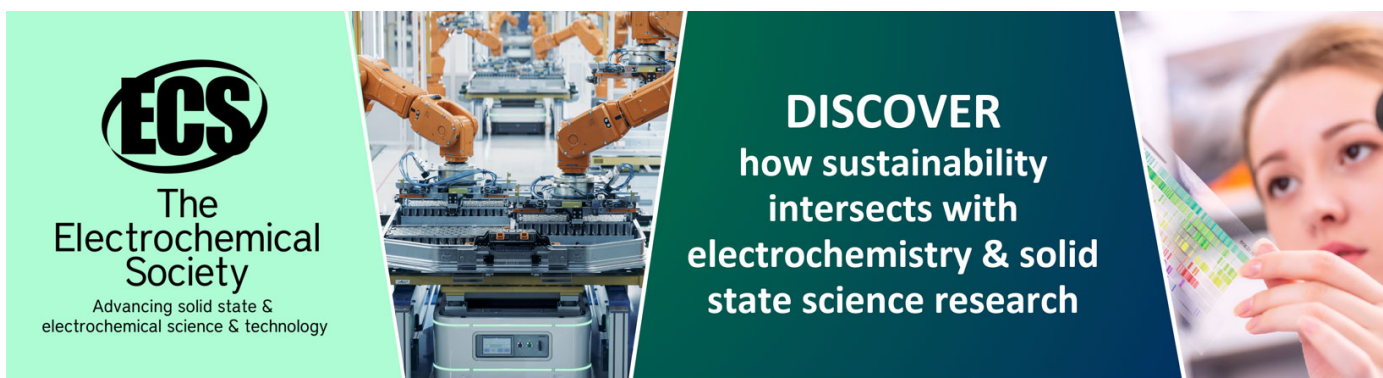
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Characterizing axial crash foldability of AHSS & UHSS sheets by means of L-profile compression tests

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Abstract. Small-scale crash tests of crash boxes have established themselves as an assessment tool for high strength materials for their application in crash-relevant structures in the automotive body. However, when investigating UHSS grades it can be seen that the performance outcome is highly susceptible to details of the crash box geometry, e.g. shape of cross section or position of spot welds, and the test setup. This may even lead to opposing crash performance ratings for the same grade if different setups are compared. In order to rule out any side effects of specimen geometry and test setup, a simpler test method is desired. If a crash box sustains plastic folding in its first fold it often also sustains the subsequent plastic folding events. Accordingly, the L-profile compression test is presented where a specimen, mimicking a quarter of the crash box cross-section, is compressed, forming a single plastic fold. The crash performance assessment is carried out by means of the so called crash index, a weighted relative measure of crack and fracture lengths within the sample, and correlated to the results of corresponding small scale tests, i.e. bending, notched tensile and hole expansion tests.

1. Introduction

Meeting both the needs for improvement of passenger safety and mass reduction has led to an increased demand for high strength steels in the automotive industry. Especially the lightweight design of crash-relevant structures presents a major challenge during the design process. The variety of available advanced high strength steels (AHSS) and ultra-high strength steels (UHSS) may render the appropriate material selection difficult. Despite the reported correlations between small-scale tests, like e.g. 3-point bending, and crash performance [1-3], actual crash testing typically cannot be avoided. Since large-scale component crash-tests are expensive and often not feasible due to the lack of a final design, small-scale model crash tests have been established during material approval. Besides the 3 point bending crash or side impact crash test, the axial crash test of crash boxes has become a benchmark when it comes to testing crash foldability of sheet materials. However, these tests are still typically expensive and very time-consuming. In addition, a multitude of different crash box cross sections (rectangular, trapezoid, hexagonal, etc.), joining techniques (spot welding, laser welding, including a closing blank at top and bottom, etc.), folding triggers (dents, holes, etc.) and test configurations (horizontal sled or vertical drop tower) has been presented. This makes comparison of test results difficult.

Recently, a quantitative assessment scheme for crash performance during axial and side impact crash tests, based on measurements of crack lengths, has been presented [2-3] allowing to compare



between different test setups, materials and sheet thicknesses. However, UHSS grades represent a challenge when it comes to the assessment of crash foldability, since different axial crash-test setups might lead to opposing results for crash performance, i.e. tests of the same sheet material might end up in perfect plastic folding or total failure (“peeled banana”) for different axial crash box designs. It seems that these kind of tests are no longer assessing the potential of the material itself but they tend to deliver an indication on the performance of the axial crash box design as well. Thus an alternative test is desired testing the ability of the material itself to form plastic folds during crushing.

It can be observed that, if a material is able to sustain the occurring deformation during primary plastic folding in an axial crash test, the material mostly sustains also the subsequent plastic folding events (Figure 1), although the crash column still may fail from global buckling or failure of the weldings due to non-optimal design of the crash box or trigger [4]. Thus the geometrical considerations of Abramowicz and Wierzbicki [5-7] are revisited. They already suggested testing only the first folding of an L-shaped segment of a crash box, called basic folding element [5], to investigate such plastic folding events. This kind of approach has recently also been applied for failure characterization of aluminum sheets [8] and for failure model validation of steel composite materials [9]. Herein we present a test setup and evaluation methodology for a compression test of an L-shaped specimen. The specimens will be compressed in a step-wise fashion and the evolution of cracks will be quantified. In addition, the test results will be related to small scale material test results in order to revisit their respective potential as an indicator for crash performance. Next to standard uniaxial tensile tests, these small scale tests also include notched tensile tests, bending tests and hole expansion tests.

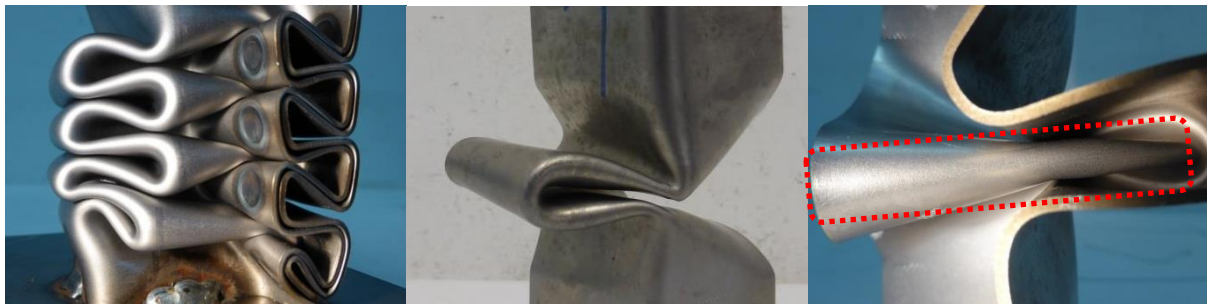


Figure 1: Folding pattern of an axial crash box (left) and compressed L-shaped profile and its primary plastic fold as seen from outside (center) and inside (encircled, right), mimicking a portion of the crash box cross-section.

2. Proposed Test Setup

The proposed test setup comprises L-shaped specimen which needs to be clamped at both ends. The sample is subsequently compressed until the primary plastic fold is fully closed (Figure 1). A first test setup for the L-profile compression test was designed to be tested in a standard uniaxial testing machine [10]. However, it needed several improvements in its clamping system since it featured only grooved plates where the specimens were inserted and no active clamping was applied. This frequently led to dislodged samples during the tests. The altered active clamping system comprises wedge-shaped clamps, suitable to be inserted into an independent side-loading hydraulic wedge grip system for uniaxial tensile testing machines (Figure 2), where the samples are clamped prior to the tests, i.e. before applying a compressive force. Exchangeable clamping jaws allow for testing of different profile opening angles and the respective chamfered edges on the inner clamping jaws enables testing L-shaped specimens of varying inner radius (e.g. bent sheets, see Figure 2, left). As regards bending of AHSS & UHSS sheets it has to be noted that usually the bendability of these grades is limited [11], leading to minimum radii which can be bent without introducing significant pre-damage. Smaller bending radii would lead to subsequent failure initiation being limited to bent regions.

The methodology is not limited to sheets bent in a press brake. It can also be applied for testing of sheet profiles manufactured by roll forming or even extruded profiles of non-ferrous metals.

The samples investigated herein exhibit leg lengths L of 50mm each, a total height h of 220mm (transverse sheet direction), a bending radius r of 6mm and a bending angle of 90° and thicknesses of 1.2 to 1.6mm. The unfolded length of the initial blank depends on the respective leg length, radius and thickness. In order to have the primary plastic fold oriented in longitudinal direction, the initial bending during sample production has to be performed in transverse direction.

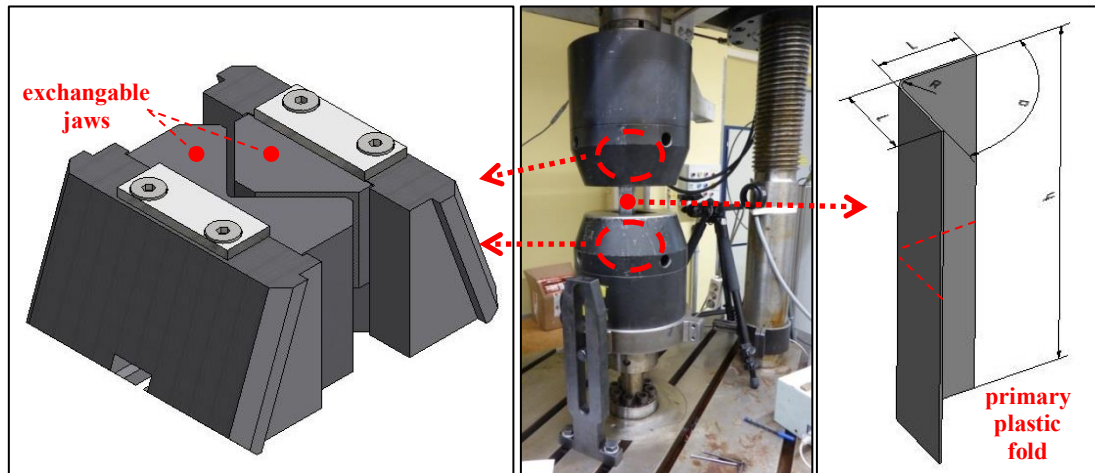


Figure 2: The proposed test setup - clamping device including exchangeable clamping jaws (left), test setup mounted in a uniaxial tensile testing machine (center) and sample geometry parameters (right).

The quantitative crash-foldability assessment for the L-profile compression tests follows the approach by Larour et al. [2]. The total lengths of small superficial (surface) cracks L_S as well as the total lengths of through-thickness (big) cracks L_B are measured after the tests. Then the so called crash index (CI) is defined according to:

$$CI = \left(0.2 * \left(1 - \frac{L_S}{55} \right) + 1.0 * \left(1 - \frac{L_B}{55} \right) - 0.2 \right) * 100 [\%], \quad (1)$$

for total possible crack length of $(L_S + L_B) \leq 55$ mm in the primary plastic fold, resulting from the specimen geometry mentioned above and its corresponding folding pattern (see Figure 1). CI of 100% means a crack-free plastic folding while CI of 0% means a totally broken fold. The crack lengths L_S and L_B are determined by visual inspection without a microscope, i.e. by the naked eye, enabling a precise inspection of the samples after the tests. Measuring L_S is obviously more subjective as compared to the determination of L_B . However, as seen in Eq. (1), surface cracks are less weighted than through-thickness cracks. A precision of ± 5 mm for the L_S is sufficient to capture the crash foldability using CI .

The tests are conducted in a step-wise manner, allowing for a depiction of CI versus the global compressive displacement and subsequent identification of the onset of cracking. The setup allows for a total intrusion of 70mm. The reported total intrusion is measured after the tests as the difference between initial height of the L-profile and final height of the folded sample.

Besides the L-profile compression tests, a series of small scale tests were performed as well in order to perform a correlation analysis according to [2], including:

- standard uniaxial tensile tests yielding ultimate tensile strength R_m and tensile elongation A_{80} ,
- bending tests in longitudinal direction using a VDA 238-100 [12] bending test setup, yielding the bending angle α_{CRACK} at crack initiation [1-2], since the standard VDA bending angle at

maximum force α_{FMAX} does not necessarily coincide with crack formation – especially for AHSS,

- notched tensile tests (notch radius 5mm) [2, 13] in transverse direction yielding the equivalent fracture strain under plane strain tension $\varepsilon_{F,PS}$ from a fracture thickness measurement in the middle of the fracture surface (as described in [2]) and
- hole expansion tests according to ISO 16630 [14] yielding the hole expansion ratio HER .

3. Results and Discussion

The proposed test setup was tested for 8 different AHSS and UHSS materials, exhibiting $R_m \geq 980$ MPa in sheet thicknesses from 1.2 to 1.6mm, totaling 22 different AHSS and UHSS sheets. The exemplarily shown grades will be referred to by their respective crash foldability level as “good”, “intermediate” and “poor”, only. The shown examples exhibit a common sheet thickness of 1.2mm.

Three steps of the step-wise testing are shown for in Figure 3. These steps represent the initiation of a plastic fold (left column), the ongoing plastic folding (middle column) and a fully closed plastic fold (right column). Next to each image of the whole sample, an additional detailed image of the plastic fold can be seen. The intrusion indicated in Figure 3 is the measured displacement after the sample has been dismantled from the test device, i.e. after springback.

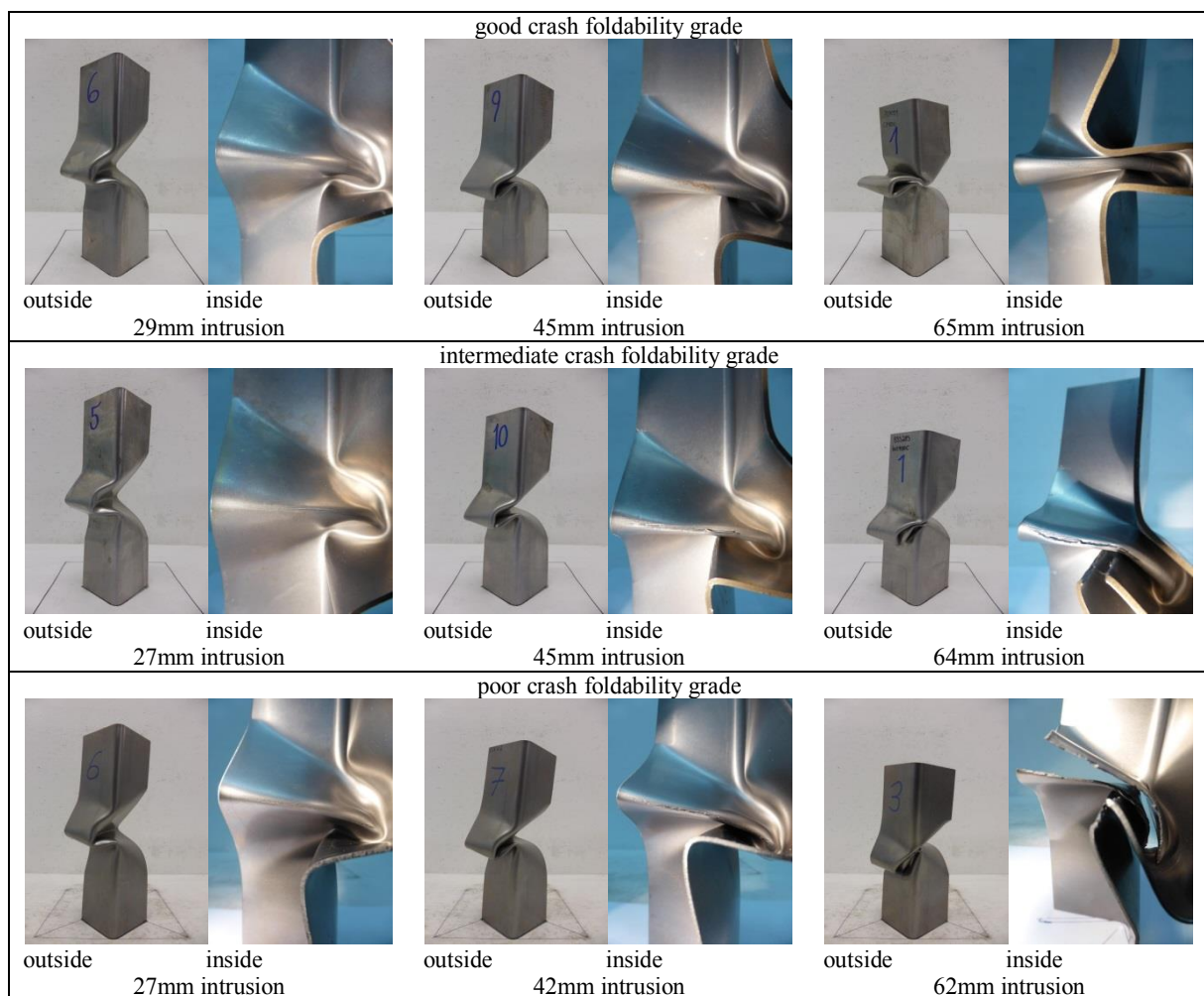


Figure 3: Examples of crushed L-profile compression samples of different UHSS grades at three different deformation steps; left image: whole sample, right image: view on inside of plastic fold.

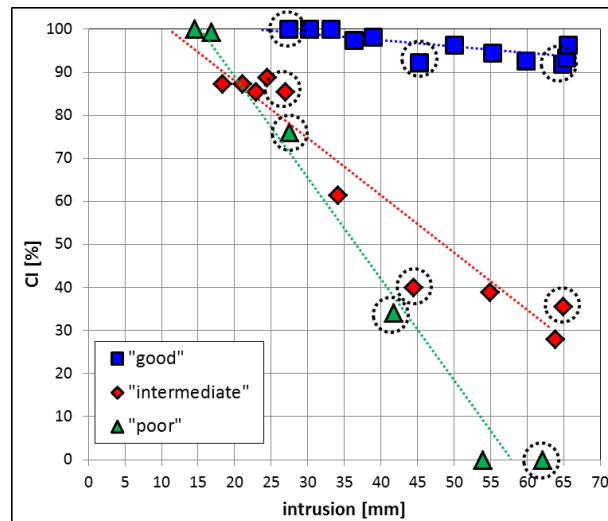


Figure 4: Crash-index CI versus intrusion after unloading of three UHSS materials; dotted lines represent the crash index decreasing rate $CIDR$ [%/mm]; encircled markers: specimens shown in Figure 3.

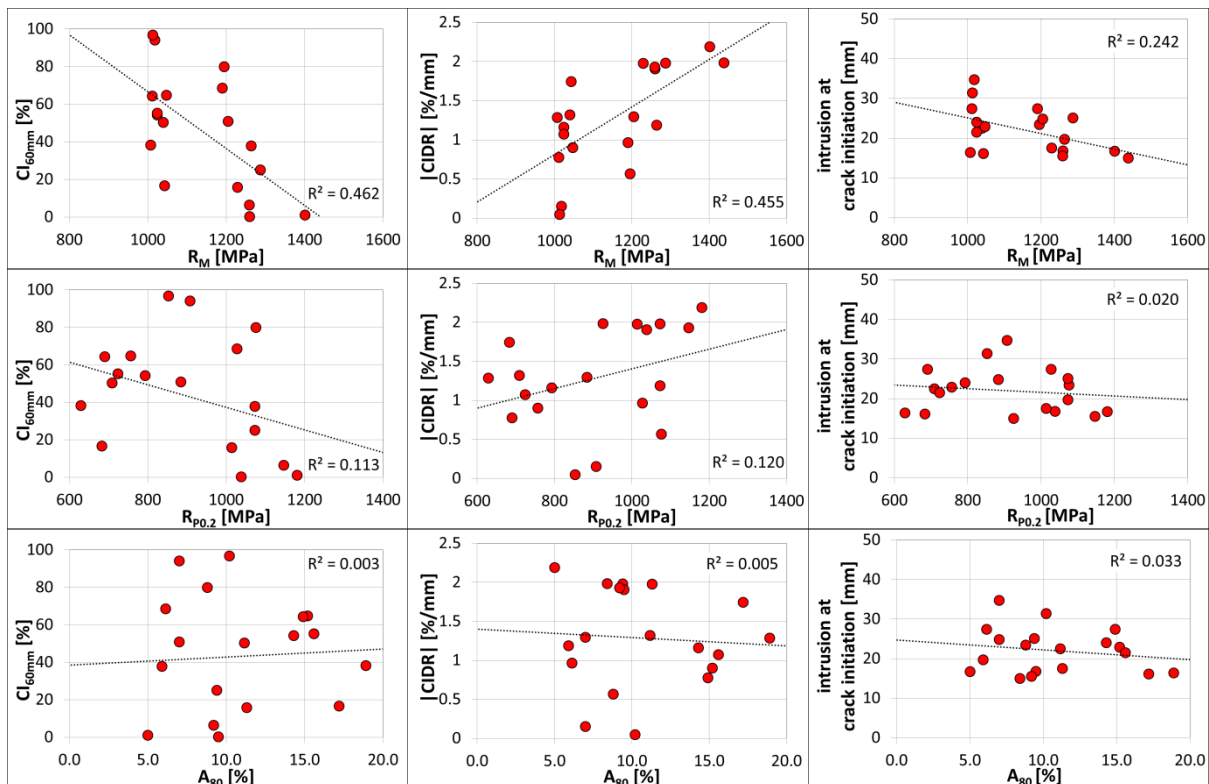


Figure 5: Crash index CI_{60mm} (i.e. at 60mm displacement, left column), absolute crash index decreasing rate $|CIDR|$ (middle column) as well as intrusion at crack initiation (right column) versus tensile test results: strength R_m (top row), yield strength $R_{p0.2}$ (center row) and tensile elongation A_{80} (bottom row).

Figure 4 shows the crash index CI according to Eq. 1 versus the intrusion for the step-wise tests of the examples shown in Figure 3. The rate of decrease of CI with increasing intrusion (dotted lines in Figure 3) is defined as crash index decreasing rate $CIDR$ according to the methodology introduced in [3]. The respective positions of the examples shown in Figure 3 are encircled at 27-29mm, 42-45mm and 62-65mm intrusion (Figure 4).

The correlations between the standard uniaxial tensile tests and the small scale tests and the results of the L-profile compression tests are shown in Figures 5 and 6. They depict the CI at 60mm displacement (CI_{60mm} , calculated using the respective $CIDR$, left column), $CIDR$ (middle column) and the intrusion at crack initiation, i.e. where CI decreases below 100% for the first time (right column) versus tensile strength R_m , yield strength $R_{p0.2}$ and tensile elongation A_{80} (Figure 5) as well as the plane strain fracture strain $\varepsilon_{F,PS}$, bending angle α_{CRACK} , hole expansion ratio HER (Figure 6).

The general trends which can be seen – in case the correlation coefficient $R^2 > 0.1$ – are a decreasing CI_{60mm} and intrusion at crack initiation with increasing $R_{p0.2}$ and R_m as well as an increasing $CIDR$ with increasing $R_{p0.2}$ and R_m (Figure 5) for the standard uniaxial tensile test results. No trend could be retrieved in relation to A_{80} . As regards the small scale tests increasing CI_{60mm} and intrusion at crack initiation could be seen with increasing $\varepsilon_{F,PS}$, α_{CRACK} and HER , while $CIDR$ is found to decrease with increasing $\varepsilon_{F,PS}$, α_{CRACK} and HER .

The low predictive capability, i.e. low correlation coefficients, of uniaxial tensile test results highlights the need for advanced testing methodologies (Figure 5). A previous investigation yielded higher correlation coefficients between CI and tensile strength for press hardened material [2]. However, there a single phase material was investigated (martensitic microstructure) whereas herein the multiphase nature of the investigated AHSS & UHSS adds considerably more variation between the different materials exhibiting e.g. the same ultimate tensile strength.

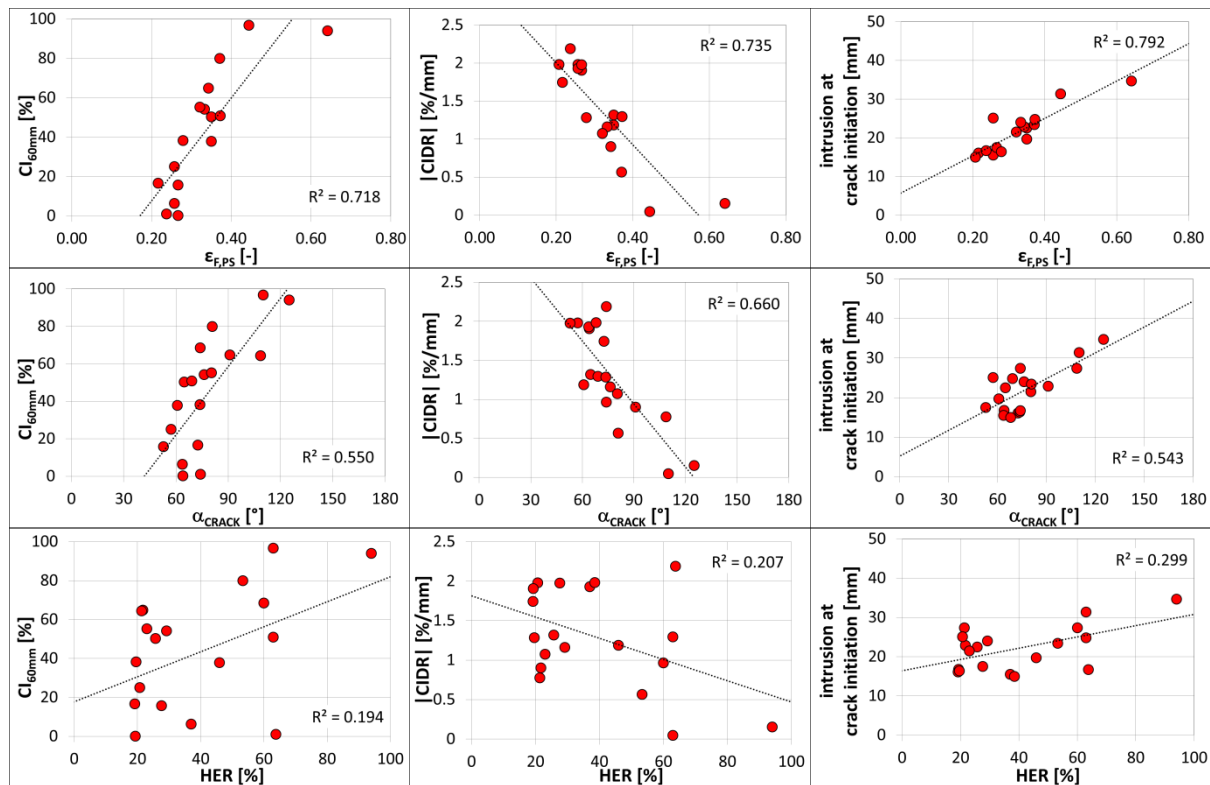


Figure 6: Crash index CI_{60mm} (i.e. at 60mm displacement, left column), absolute crash index decreasing rate $|CIDR|$ (middle column) as well as intrusion at crack initiation (right column) versus advanced small scale tests: plane strain fracture strain $\varepsilon_{F,PS}$ (top row), bending angle α_{CRACK} (center row) and hole expansion ratio HER (bottom row).

Non-surprisingly, the correlation coefficients are higher for more advanced small scale tests (Figure 6). However, only tests depicting the plane strain condition prior to cracking in the plastic folds (bending and notched tensile tests) yield reasonably good correlation coefficients as compared to hole expansion tests, depicting uniaxial tension, where again only weak correlations are found.

4. Conclusions

The L-profile compression test is a very simple test to assess the axial crash foldability of the sheet materials themselves, i.e. without the influences of the crash box design. Therefore this test enables ranking materials according to their crash foldability.

If a material shows poor crash foldability in the L-compression tests, actual testing of axial crash boxes might be omitted, resulting in considerable savings of time and costs. However, it has also to be stated that this test does only show the potential of a material to sustain plastic folding events. Whether a component produced from this material will actually show plastic folding during a crash event is then also subject to the crash-box design and the loading scenario and cannot be judged on the results of the L-compression test alone.

Prior to small-scale model-component crash tests and large-scale crash tests, the L-profile compression test may also be established as an additional pre-step reducing time in the material selection process for AHSS and UHSS sheets.

The presented crash index CI enables quantifying crash foldability based on the observed crack and fracture pattern. In addition the crash index decreasing rate $CIDR$ is an indicator for the resistance to crack propagation during crash folding. L-profile compression test results are shown to correlate well with plane strain based small scale material tests, i.e. bending tests and notched tensile tests, while they do not correlate well with small scale tests depicting different loading scenarios, e.g. hole expansion tests or results from standard uniaxial tensile tests.

In addition, the L-profile compression test also has potential for numerical damage model validation due to its simple geometry, boundary and contact conditions in contrast to simulations of axial crash boxes or 3-point bending crash tests, i.e. no complicated crash box design, no welding, etc.

As mentioned above, the presented application is just one specification of the test methodology, which may be also applied for testing of e.g. roll-formed sheet profiles.

Due to the simple specimen geometry, a follow-up investigation of the presented setup and test method for hot-formed L-shaped profiles is being considered to study the crash foldability of press-hardened steels during their material development process as well.

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