Published: International Conference on Steels in Cars and Trucks, June 18-22, 2017, Nordwijkerhout; © Steel Institute VDEh

On the Relation of Local Formability and Edge Crack Sensitivity

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1 Summary

The use of high and ultra high strength steels requires an exact knowledge of the forming behavior of the material, both in the base material and in the edge region. This increases significantly the number of necessary tests and thus the total number of samples for a comprehensive material characterization.
The aim was to reduce the number of tests by identifying possible correlations. For this reason forming analyses were carried out using an optical strain analysis system (OSAS) for further detailed strain analysis. Thus, two sets of samples, bainitic and ferritic hot rolled steel sheet as well as dual and complex phase cold rolled steel sheet, were investigated employing the test methods tensile test and different edge crack tests.
The results show that the samples of the first set are identical in terms of ductility, as obtained by optical strain analyses (OSA) of tensile tests and hole expansion tests on samples with eroded edges, but differ in fracture toughness as represented from hole expansion tests on punched samples. Regarding the second set, one of the samples shows higher total elongation in tensile test as a result of a large global strain contribution and only a small contribution from local strain as OSA shows. The fracture toughness obtained from hole expansion tests on punched samples of this material is significantly lower.
In conclusion, the results demonstrate that the assessment of ductility depends on the chosen virtual gauge length and thus is not necessarily represented by total elongation. The local strain of the tensile tests obtained by OSA shows a fairly good correlation to the results of the hole expansion tests with eroded edges. Unfortunately, a corresponding correlation to the results of hole expansion tests with shear cut edges cannot be found. Summarized, the results demonstrate that only a combination of high local strain and high fracture toughness leads to a high formability of punched edges. Prospectively, these two properties have to be taken into account individually for material characterization and future material development.

2 Key Words

Steel, edge crack sensitivity, hole expansion ratio, local formability, global formability, tensile test, ARAMIS-System, strain analysis

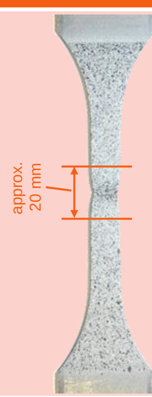
3 Introduction and Motivation

Test methods for material characterization are used in order to obtain knowledge for material behavior under various load cases. In addition to the standard test methods such as tensile and Nakajima FLC tests, which are exclusively applicable for a description of the formability of the base material, the formability of the edge is evaluated employing so-called edge crack tests.

Material specification standards such as DIN EN 10346 and VDA 239-100 contain strain values which have been determined using a global measurement. Depending on the material thickness, samples with an initial measurement length and thus a strain reference length of 80 mm or 35 mm are used. The strain detection can be performed either tactilely by means of measuring transducers or optically using a laser extensometer or ARAMIS system. Dual-phase steels generally show good global formability as compared to complex phase steels. The reason is the good transfer of the forming to neighboring material areas due to a high strain hardening. Owing the lower hardness differences in the individual phases, complex phase steels have significantly lower edge crack sensitivity in comparison. In particular, this property offers advantages for applications where the shear cut edge of components is subjected to high elongations.

As in [1], for example, a direct relationship between global strain parameters of tensile tests and characteristic values derived from edge fracture testing methods could not yet be determined both over material classes and within a material class. Therefore, the aim of the investigations is to identify correlations between locally determined strain values of the base material and the edge crack characteristics. These local strains are obtained from strain analyzes of tensile specimen using the OSAS ARAMIS. The strain range considered in these analyzes comprises an order of magnitude of approximately 20 mm, see Table 1.

Table 1: Global and local strain measurement using the tensile test

	base material example: tensile test	
	global measurement	local measurement
gauge length		

4 Material and its Mechanical Properties

The investigations are carried out on materials from the following material classes:

- bainitic hot-rolled strip in a sheet thickness of 4.0 mm: HR-BS800
- ferritic hot-rolled strip in a sheet thickness of 4.0 mm: HR-FS800
- complex phase steel (cold rolled strip) in a sheet thickness of 2.0 mm: CR-CP800
- dual phase steel (cold rolled strip) in a sheet thickness of 1.7 mm: CR-DP800

All materials used have a tensile strength of more than 780 MPa (see table 2). The bainitic and ferritic steel are microalloyed and thermo-mechanically hot rolled. The mechanical properties are sufficient for forming applications such as mobile crane constructions and complex parts like suspension components [2].

Complex phase steel consists of different microstructural proportions. Bainite is predominantly contained, ferrites are present in small amounts and only traces of other phases. The homogeneous, fine-grained structure is adjusted by defined temperature control at the hot-dip galvanizing. Since the complex phase steel already has a high yield strength in the unformed state, the material is particularly suitable for components which require a high strength that cannot be obtained by work hardening. Moreover, due to its low edge crack sensitivity, the complex phase steel is used when complex forming operations are carried out in edge regions in order to pull collars for instance.

The dual phase steel is a steel with a two-phase microstructure consisting of a ferritic (soft) basic structure in which islands of a martensitic secondary phase are embedded [3].

Table 2: Mechanical properties of investigated materials coming from standards as well as material data sheets [2], [4]

material	yield strength $R_{p0,2}$ [MPa]	tensile strength R_m [MPa]	total elongation A_{80}^{*} / A_5^{**} [%]
HR-BS800	≥ 680	800 – 980	≥ 12**
HR-FS800	≥ 680	800 – 980	≥ 12**
CR-CP800	570 – 720	780 – 920	≥ 10*
CR-DP800	440 – 540	780 – 900	≥ 14*

5 Experiments for Determining Edge and Base Material Formability

In the following, the test methods for determining the formability of the base and edge material are briefly described.

5.1 Material Formability

Tensile Test

The tensile tests transversely and longitudinally to the rolling direction are carried out in accordance with SEP1240 [5], which means a constant strain rate is used over the entire test. Proportional tensile tests (called A_5 samples) are used for materials thicker than 3.0 mm and tensile test specimens (called A_{80} samples) with a constant test length of 80.0 mm for material thinner than 3.0 mm. In order to perform a local strain analysis, a stochastic pattern is applied to each sample before drawing. With the aid of an OSAS, the strain is evaluated along cutting lines, which are oriented centrally in the direction of the longitudinal axis of the specimen, as shown in figure 2.

Hole expansion according to ISO 16630

The hole expansion test according to ISO 16630 [7] is currently the only standardized test for the determination of edge crack sensitivity. In this test, a hole with a diameter of 10 mm is punched into the sheet metal specimen (relative cutting clearance: 12 %) by shear cutting and is subsequently expanded using a conical punch (cone angle 60°). The expanding is stopped by the operator as soon as a crack through the entire thickness of the sheet metal is detected visually. Consequently, the results of this test are highly dependent on the perception and response speed of the operator [6]. The test result is given by the so-called hole expansion ratio, which is calculated as the ratio of the hole diameter increase to the initial hole diameter.

Hole expansion with Nakajima punch

In the case of the hole expansion test with Nakajima punch the test setup for determining a forming limit curve is used [8]. The test procedure is pretty similar to the ISO 16630 hole expansion test concerning the process steps and parameters. A hole with a diameter of 20 mm is punched by shear cutting into the sample. Afterwards this hole is expanded with a hemispherical Nakajima punch (diameter: 100 mm). The test is immediately stopped as soon as a crack extending through the entire thickness of the sheet metal can be detected. The crack initiation occurs more abruptly in the hole expansion with Nakajima punch than in the ISO 16630 hole expanding test. For this reason, a crack width correction, as presented in [9], should be performed in the evaluation. The result is the hole expansion ratio described above. However, in contrast to the ISO 16630 hole expanding test, a stochastic pattern can be applied to the surface of the sheet metal before forming and a detailed strain analysis for the region of the specimen close to the edge can be performed using the ARAMIS optical measurement system from the company GOM. The crack initiation and the hole expansion ratio can be detected automatically and determined by means of an evaluation macro based on Visual Basic, which contains defined crack criteria. As a result, so-called polar diagrams can be generated that visualize the strain distribution along a circle with a defined distance from the punch edge over time [10].

6 Test Results and Discussion

In Figure 1 the results of the global strain measurement are shown as stacked columns for the tensile specimens longitudinally and transversely oriented to the rolling direction. The orange part of the column represents the uniform elongation (A_u) and the blue part the necking strain (A_n). The total column height thus corresponds to the total elongation.

The bainitic and ferritic grades show roughly equal proportions of uniform and necking elongation. Total elongation is about the same for both. CR-DP800 1.7 mm has the highest uniform elongation and comparatively low necking elongation. The CR-CP800 2.0 mm shows a slighter degree of uniform elongation as well as total elongation.

The results in Figure 1 also demonstrate the restrictions when comparing ductility on basis of common tensile test data: A comparison of total elongation is only allowed on the same strain reference length. This condition is not given, since due to the sample thickness, different specimen shapes are applied.

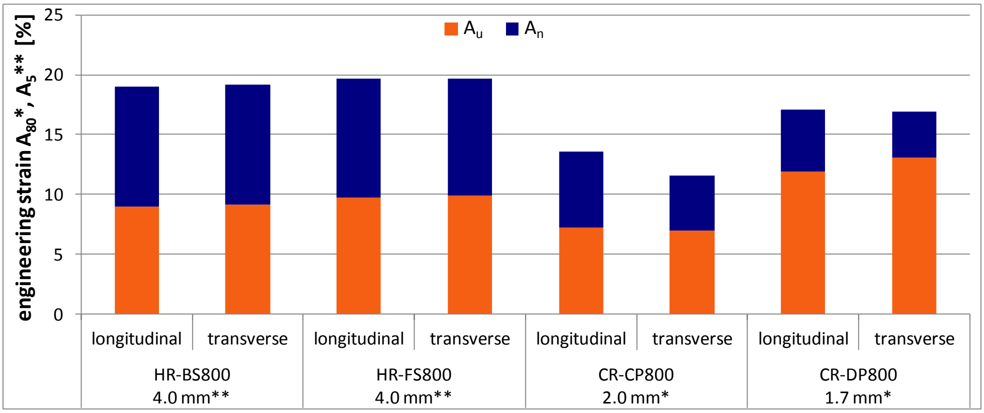


Figure 1: Results of uniform elongation (A_u) and necking strain (A_n) as a stacked column of global strain measurement from tensile tests; total column height represents total elongation

For the local strain evaluation, OSA on tensile samples were carried out. Cutting lines along the sample longitudinal axes are generated and exported (Figure 2). These strain profiles are fitted with the peak function according to Gauß. To define a baseline, the corresponding anchor points were created using the method "second derivation". The area between the fitted curve and baseline is defined as the amount of local strain (blue). This strain portion corresponds to the strain within the area of localized necking. Below the baseline within the boundaries given by the intersections of fitted curve and baseline, the amount of strain is defined as “global strain”. This strain portion corresponds to the sum of uniform elongation and diffused necking. In each case the results of the global and local strain portions are standardized on the distance of the corresponding intersection points.

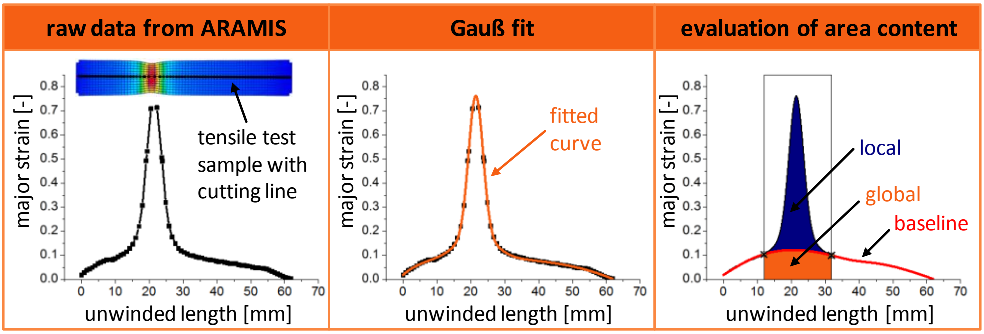


Figure 2: Cutting line in the ARAMIS project (top left) as well as the cutting line sequence (bottom left); Fit with Gauß peak functions (middle); Determination of the local and global strain portions between the intersections of the fitted curve and the generated base line (right)

In Figure 3, representative strain profiles along the cutting lines for each material are shown both individually and superimposed with respect to the strain peaks. It can clearly be seen that the materials except the dual phase steel show a very similar strain distribution with a pronounced necking area. In comparison, the dual-phase steel has a significantly higher global strain proportion. But the area of the localized necking is small.

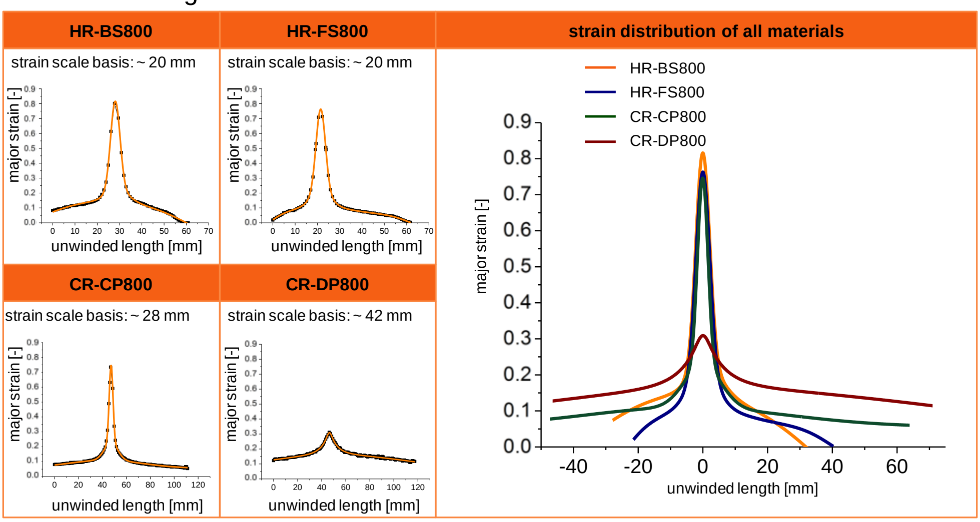


Figure 3: Exemplary strain distribution for each material at the time “last picture before crack” (left); Comparison of the strain distribution of all materials (right)

The results of the OSA using the Gauß peak function are illustrated in Figure 4 as stacked columns. The global strain is represented by orange columns, while blue-colored columns represent the local strain portion.

The data plotted in Figure 4 differ from those in Figure 1. The reason is that the virtual strain gauge as shown in Figure 3 is smaller than given in standard tensile tests. Consequently, the fraction of strain deriving from the necking region is comparatively larger. As the gauge length depends on the extent of the localized necking region, the data in Figure 4 allows comparing the ductility of the samples more specifically.

The bainitic and ferritic grades show the highest overall elongation, which is ductility, in case of local strain measurement. Furthermore a difference between these two steel grades is apparent with regard to the local and global strain portions. Both strain portions are slightly higher for HR-FS800. CR-CP800 2.0 mm has consistently a higher overall elongation as well as a local strain than the CR-DP800 1.7 mm. The percentage of local strain in the overall elongation is, in case of the CR-CP800 2.0 mm, at a level similar to the bainitic and ferritic materials. In case of the CR-DP800 1.7 mm, the global strain is by far the largest share of the overall elongation.

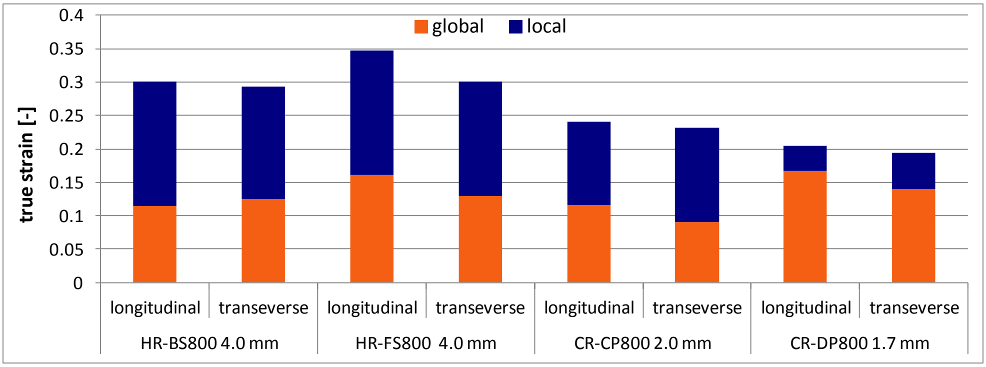


Figure 4: Results of the local strain measurement using OSAS derived from tensile tests as stacked columns consisting of global and local strain portions

Strains up to material failure are also to be determined in edge crack tests by means of OSA. Figure 5 shows representative polar diagrams of all four materials, both with punched and eroded edges. The diagrams are determined with the aid of the edge crack test hole expansion with Nakajima punch. The time-change of the major strain of the first circular cutting line is shown. This circular cutting line has a distance of about 2 mm from the physical edge [10].

The material-specific strain characteristics are obvious. Both the bainitic and the ferritic steel exhibit an anisotropic material behavior that becomes visible through strongly pronounced strain localizations longitudinal and transverse to the rolling direction. A weak anisotropic behavior is also recognizable for the CR-CP800. The dual-phase steel has a very homogeneous strain distribution along the edge. Cracks occur almost spontaneously, without a preferential cracking position. Moreover, with the exception of the CR-CP800, eroded edges allow a significantly higher forming capacity. A clear difference is visible in the strain behavior of HR-BS800 and HR-FS800 considering punched edges. Punching in the case of the HR-FS800 reduces the forming capacity to a great extent though both steels have the same forming capacity when the edges are eroded. A special case is represented by the polar diagram of the CR-CP800. The hole expansion ratios for the punched and eroded edges are almost identical. The conclusion is that the steel sample is not sensitive to edge cracking under the given circumstances, i.e. thickness and the specific stress state given in the Nakajima setup.

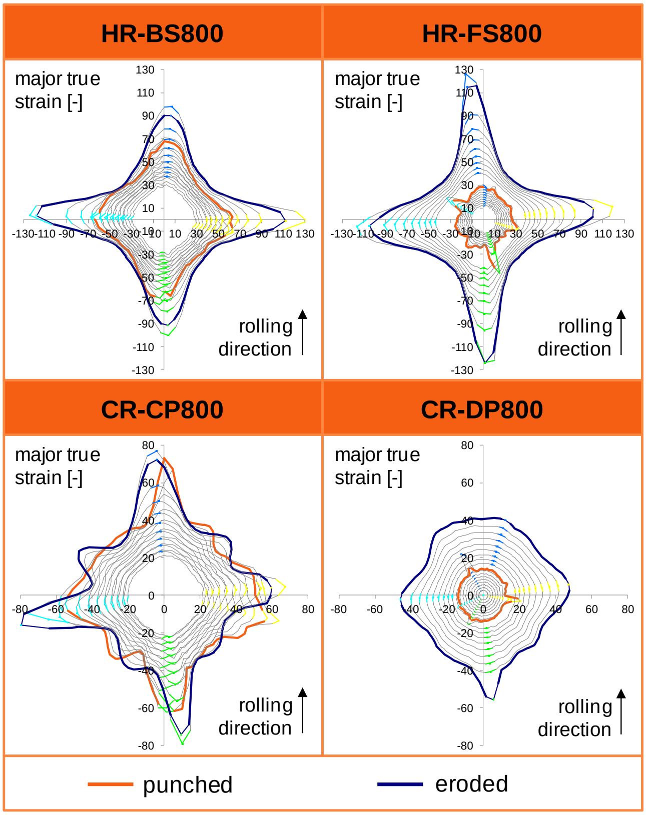


Figure 5: Polar diagrams determined by means of the test hole expansion with Nakajima punch of all four materials with stamped and eroded edge

In Figure 6 the results of the OSA derived from the tensile tests as well as the results of two different edge crack test methods (Nakajima setup as discussed above and a conical punch according to ISO16630) with punched and eroded edges are presented as a whole.

A correlation of the local strain portion and the edge crack characteristics, which have been determined on eroded samples, can be detected: samples of a comparatively high local strain feature also higher edge formability. Considering the edge formability of punched edges such a clear correlation cannot be identified. Both edge crack tests on punched samples tend to show a reciprocal behavior to the global strain values of the tensile test.

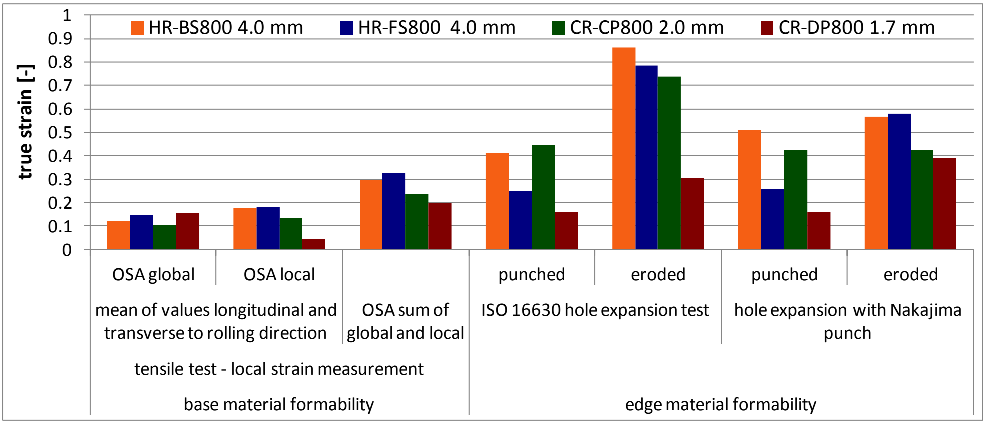


Figure 6: Results of OSA of the tensile tests as well as results of two edge crack test methods

A better understanding of the details in the results is achieved when regarding the hot rolled and cold rolled samples separately as presented in Figure 7. Regarding the hot rolled samples, identical results in the local and global strain contributions in tensile tests as well as edge crack tests with eroded edges are obtained. Thus, these results represent the ductility of the samples. Differences between the hot rolled samples are identified in hole expansion tests on punched samples. The interpretation is that only latter experiments test a material property that includes fracture toughness issues. As presented in [11] this is the crack propagation from the strain hardened shear cut edge into the bulk material already at early stages of the expansion process. Consequently, HR-FS800 is regarded to be more sensitive to edge cracks at the same ductility level than HR-BS800.

Comparison of the cold rolled samples in Figure 7 (right) show that CR-DP800 has a slightly higher global strain contribution but the local strain contribution is lower than in CR-CP800. Concerning the Nakajima hole expansion test the virtual gauge length is twice as large as in the ISO test and thus the proportion of the global strain is higher. As a result, the determined strain in Nakajima hole expansion test on eroded samples is comparatively high in case of CR-DP800. Again, the results from tensile test and hole expansion tests on eroded samples can be explained by the ductility of the samples. Regarding the hole expansion tests on punched samples, the CR-DP800 samples deliver significantly lower values than CR-CP800 samples. Hence, these results represent the lower fracture toughness of the dual phase steel compared to the complex phase steel. This is a well known difference between dual phase steels and complex phase steels that is explained by the homogeneity of the microstructure, compare e.g. [12].

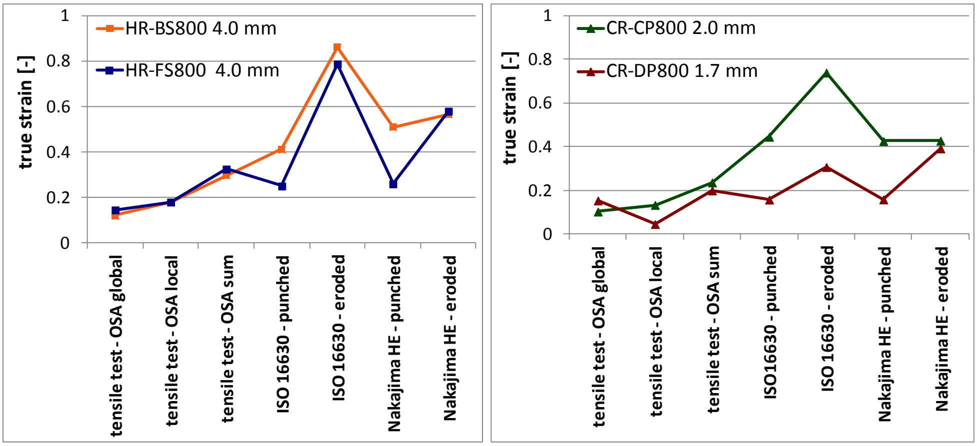


Figure 7: Results from Figure 6 separated in the 4 mm hot rolled samples (left) and the cold rolled samples 1.7 to 2.0 mm in thickness (right)

7 Conclusion and Outlook

The local strain of the tensile tests obtained by optical strain analyses (OSA) shows a fairly good correlation to the results of the hole expansion tests with eroded edges. Unfortunately, a corresponding correlation to the results of hole expansion tests with shear cut edges cannot be found. This is due to the fact that the edges are highly strain hardened and predamaged. Thus, failure occurs due to early propagation of cracks that have their origin at the edges. Consequently, the results are highly influenced by fracture toughness issues that do not necessarily correlate to ductility. However, a small difference in the results of hole expansion tests with punched and erode samples is interpreted as high fracture toughness.

The outcome is proved by two sets of samples:

The first set is hot rolled low carbon steel sheet that is identical in terms of ductility as obtained by OSA of tensile tests and hole expansion tests on samples with eroded edges but differs in fracture toughness as demonstrated from the hole expansion tests on punched samples.

The second set of samples consists of cold rolled multi phase steel sheet. One of the samples shows higher total elongation in tensile test as a result of a large global strain contribution and only a small contribution from local strain as OSA shows. The fracture toughness is significantly lower. This combination results in very low hole expansion ratio for punched samples.

Summarized, the results demonstrate that only a combination of high local strain and high fracture toughness leads to a high formability of punched edges. Prospectively, these two properties have to be taken into account individually for material characterization and future material development. Different kinds of test methods are possible for the determination of local strains, for example tensile test or forming limit curve specimens. However, fracture toughness has to be determined by edge crack tests since the influence of punching on the material is to be evaluated.

8 Acknowledgements

The authors gratefully thank Mr. Tuan Anh Nguyen, who put a lot of effort into his Bachelor thesis.

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