An approach to describe edge ductility

V Kesti1*, M Folmerz2, R Vierelä3, P Rautio3, R Ruoppa3, P Plosila4 and A Kaajalainen4
1 SSAB Europe, Raahe, Finland
2 SSAB Europe, Borlänge, Sweden
3 Lapland University of Applied Sciences, Kemi, Finland
4 Materials and Mechanical Engineering, CASR, University of Oulu, Oulu, Finland
*vili.kesti@ssab.com

Abstract. One of the challenges of utilizing advanced high-strength steels is their limited ability to withstand the forming of cut edges. Large production quantities of parts often lead to mechanical punching/shearing processes in blank preparation, providing a challenging starting point for forming processes. The most commonly used edge ductility test is the ISO 16630 hole-expansion test to describe stretch-flangeability properties. However, this method has been widely criticized for its large-scatter, unreliable results and the fact that it covers only a certain stress-strain state of cut edge forming. In addition, it does not provide enough data to be reliably used in forming simulations to predict edge failures. This paper presents an approach to create a more comprehensive way of describing overall edge ductility. Multiple edge forming test methods coupled with digital image correlation (DIC) were selected in order to investigate different edge loading scenarios in both open and closed trim line forming situations. Data regarding limiting local strain before cracking was collected for several steel grades, and results are gathered in 2D and 3D “Edge FLC” -figures. Attempts to utilize these results for simulation purposes are also presented. Results indicate that this approach can be useful to evaluate overall edge forming limits.

1. Introduction
The usage of advanced high-strength steels (AHSS) in car and truck parts has significantly increased in the last 15 years. Simultaneously, the complexity and overall demand for parts, their production and final performance has been increasing. For example, hot-rolled steel grades are often used in complex chassis components with mechanically cut blanks, followed by challenging forming. Cutting creates a work-hardened zone, that is, a shear-affected-zone (SAZ) [1], with high local strains, initial voids and even microcracks due to the intense mechanical shearing process. Therefore, the sheared edge often shows much lower formability than the base material. One of the major challenges to fully utilize advanced high-strength steels in these applications has been their limited ability to withstand the forming of mechanically cut edges. Another challenge is the difficulty of comprehensive edge formability characterization and lack of reliable tools to predict failures in simulation. For example, the traditional forming limit curve (FLC) can overestimate material properties in edge formability [2,3], leading to crack formation in production. Therefore, it is important to have a proper method of characterizing edge formability in a reliable and comprehensive way.

Edge ductility is most often described as a hole-expansion ratio according to the ISO 16630 hole-expansion test [4]. During the past 15 years, this method has been comprehensively investigated but also majorly criticized due to its large scatter, unreliable results and the difficulty of obtaining the same results between different laboratories [5-9]. One major limitation of the ISO 16630 test is that it covers
only one stress-strain state of cut edge forming [9,10]. Depending on part design, sheared edges can be formed in a variety of different loading scenarios during actual part production and thus multiple different test methods have been created over the years. Schneider et al. [11] have gathered an overview of different methods, including an approach to describe different loading scenarios in a variety of tests by strain gradient. One approach has been presented by Frometa et al. [12], who showed that during edge forming, steels with greater fracture toughness create higher strain at fracture, together with a lower cutting clearance sensitivity.

In this paper, an approach is presented to describe overall edge ductility, both from the perspective of the steel development phase in order to compare different steel concepts as well as the part design phase. Multiple steel grades are studied in various loading situations, together with the possibility of utilizing the results for simulation purposes. One major point of interest is to study the possible differences between materials at the same strength level in different loading scenarios: is the ranking of the materials the same in all tests or will it vary depending on the loading case? Five different edge forming test methods coupled with digital image correlation (DIC) were selected in order to investigate multiple edge loading scenarios in both open and closed trim line forming situations. The main idea is to cover a wide scope of loading situations, including forming in- and out-of-plane. In addition to different loading situations and the possibility of DIC, the tests were selected for easy accessibility (no special tools for cutting) and flexibility of sample preparation (the possibility to use different cutting clearances, sheet thicknesses and steel grades). Data concerning the limiting local strain before cracking was collected for several steel grades, and the results are shown in a maximum major strain comparison chart together with 2D and 3D “Edge FLC” -figures. These figures can also be used to evaluate the formability against simulation results. The strain path was also detected for each test setup to describe the whole loading scenario.

2. Experimental
In total six hot-rolled 3 mm steels were selected for the testing, including three grades for 355 MPa and three for 700 MPa yield strength level. For the minimum 355 MPa level, a standard S355J2 was selected as the basic standard material together with two different concepts of thermomechanically (TM) hot-rolled S355MC steels, named S355MC(1) and S355MC(2). The two latter materials exhibit an approx. 50 MPa higher yield strength than the standard material, while elongation levels are very similar for all three steels. For the 700 MPa materials, three different TM hot-rolled steels were investigated: standard S700MC(1), trial S700MC(2) and the recently developed Docol 800HHE advanced high-strength steel. The mechanical properties of the investigated materials are shown in Table 1.

| Material         | R_p0.2 (MPa) | R_m (MPa) | A_s (%) | A_g (%) |
|------------------|--------------|-----------|---------|---------|
| S355J2           | 370          | 540       | 29      | 14      |
| S355MC(1)        | 430          | 500       | 31      | 13      |
| S355MC(2)        | 420          | 495       | 31      | 14      |
| S700MC(1)        | 750          | 850       | 19      | 9       |
| S700MC(2)        | 720          | 840       | 15      | 6       |
| Docol 800HHE     | 705          | 800       | 21      | 9       |

Five different test methods were selected for the actual test matrix: hole-expansion with spherical Nakajima punch (NHE) and flat punch (KWI), tensile test with punched hole (HTT), a double-bending test (DBT) [13] and a Diabolo-test [14] (Figure 1), with the three first having a closed trim line and the latter two an open trim line for the cut edge. The NHE, KWI and Diabolo tests were conducted in an Erichsen sheet metal testing machine with 600 kN blank holder force and 0.5 mm/s punch speed. NHE tests were performed with a hemispherical punch (diameter 100 mm) with multipurpose grease lubrication on the punch side and a blank diameter of 215 mm. KWI tests were conducted with a flat
punch (diameter 50 mm) and sample size of 150 x 500 mm (three tests per sheet with 150 mm separation). The KWI test had 0.1 mm Teflon foil with multipurpose grease on both sides of the foil as lubricant. The Diabolo test had a special diabolo-shaped punch with a 20 mm radius, a blank size of 30 mm x 215 mm and no lubrication. DBT was performed with an Amada HFP 130-3 press brake with a punch speed of 1.0 mm/s, lower tool width of 40 mm and punch radius of 10–20 mm depending on material and flange height (10–18 mm). Different flange height/radius setups were used in order to obtain a wider scope of strain concentration situations, aiming for cracked specimens. The blank size in DBT was 145 mm x 145 mm. HTT was conducted with a Zwick Z250kN tensile testing machine, and the loading rate on the yielding area was 30 MPa/s and the speed at the end of the test was 0.005/s. Sample dimensions were 40 mm x 290 mm. For the sake of comparison, an ISO 16630 standard HER test without DIC measurement was conducted for all materials.

![Figure 1](image.png)

**Figure 1.** Test methods (a) NHE, (b) KWI, (c) HTT, (d) DBT, (e) Diabolo, (f) ISO 16630 and (g) edge strain components.

The holes for NHE, KWI and HTT were punched with the same tools as the ISO 16630 standard requires, with a 10 mm hole diameter and 12 % cutting clearance in an Erichsen forming machine. The Diabolo and DBT samples were cut in a CNC power shearing machine with 20 % cutting clearance. For each test, a minimum of five repetitions were performed, and for some tests, even more data is included into the analysis. All test samples were painted with a stochastic paint pattern and recorded with the GOM Aramis optical strain measurement system (frame rate of 10 Hz). Local point strains just before cracking were measured for three different edge strain components according to Schneider et al. [11]: $\varepsilon_1$ (thickness strain), $\varepsilon_2$ (minor strain) and $\varepsilon_3$ (major strain), shown in Figure 1(g). Strain analysis was conducted as close to the edge as possible with a facet size of 2.1 mm x 2.1 mm.

Different loading cases of these five tests were introduced and computed by Schneider et al. [11] and are schematically presented in Figure 2. Strain components $\varepsilon_1$, $\varepsilon_2$ and $\varepsilon_3$ are presented as simplified strain gradients starting from the edge, with the Y-axis showing the major strain component and X-axis the distance from the edge. The ISO 16330 test is also shown (Figure 2(f)) for comparison. The strain gradients are simplified, meaning that the absolute value of the major strain together with the depth of the gradient can vary from case to case, but currently only shows the basic trend. For example, the NHE and ISO tests show similar strain gradient profiles, but it is evident that, for example, the $\varepsilon_2$ component will have a distinct depth of strain gradient due to different test punch geometry. Tests were selected to provide different loading scenarios for the edge, including both in- and out-of-plane situations. In addition to different strain gradient profiles, different strain concentration profiles for $\varepsilon_3$ components along the cut edge were also selected by the test method. DBT, Diabolo and HTT tests force the strain to localize geometrically due to test geometry, while NHE and KWI create an initially uniform strain concentration around the hole, similar to the ISO16630 test. The strain will localize in these tests as well, but it will happen due to the strain localization tendency of each material, not by forcing the strain to localize by tool geometry as in the three tests mentioned earlier. One aim of the tests was also to include both open and closed trim lines into the test matrix: DBT and Diabolo representing the former and NHE, KWI and HTT the latter.
3. Results and discussion

3.1. Max local major strain

First, only data regarding major strain component $\varepsilon_3$ was collected from the tests to describe the absolute maximum local strain before crack formation. One goal of this approach was to simplify the results and to find out if the materials would end up being ranked in the same order in different tests when considering just maximum local strains. Figure 3 presents the results for maximum local major strain, except for ISO 16630, for which results are presented as basic hole-expansion ratios (with log scale) due to lack of DIC measurements. For materials in the 355 MPa level, it is evident that standard S355J2 creates much lower ISO HER and maximum local strain values compared to TM hot-rolled materials. When comparing two TM hot-rolled 355 MPa materials, it can be concluded that maximum local strains in NHE and KWI are ranked in a similar order than in the ISO HER test, with version 1 being better than version 2. However, in the rest of the tests, S355MC(2) shows higher local strains than S355MC(1). This indicates that a certain material could be optimal in one loading scenario, but for another scenario, another material would be a better choice. To conclude: if relying only on one test method, materials could be ranked in the “wrong” order. When comparing 700 MPa strength level materials (Figure 3(b)), the same ranking of the materials stays through all test methods: Docol 800HHE showing superior maximum strains compared to S700MC(1) and S700MC(2). It is still important to note that HTT provides a statistically similar level of results for all 700 MPa grades. This leads to the fact that if these materials are only tested by HTT, the excellent edge ductility behavior of Docol 800HHE in all other situations could be completely missed. According to the results, it is very difficult to create a comprehensive description of the edge ductility property by performing only one test.

Figure 3. Max local major strain [$\varepsilon_3$] values for different tests: (a) 355 MPa and (b) 700 MPa materials. **ISO HE test values are converted into log scale from [%].
3.2. 2D Edge FLD

In order to use the minor strain component in evaluation as well, “2D Edge FLD” was created to visualize the data in a similar manner to traditional forming limit diagrams. The thickness direction strain component $\varepsilon_1$ is still neglected and only the $\varepsilon_1$ and $\varepsilon_2$ components were used as major and minor strains, respectively. Results for both material groups are presented in Figure 4 (a-f). This approach provides a larger amount of information about material behavior in the different tests. As can be seen from the results, all selected tests provide compressive strains for minor strain. It is also evident that relative scatter in minor strain values is much higher than for the major strain within the same test method. For the very moderate edge ductility material S355J2, the major strain for all tests seems to achieve a similar level, even though the test methods create different minor strain values, varying from -0.01 to -0.21. This indicates that the S355J2 material tolerates only a certain level of strain along the edge in different loading scenarios. On the other hand, S355MC(2) shows a trend of increasing major strain with higher compressive minor strains. It can be noted that HTT creates the lowest level of major-minor strain combination for S355MC(1), S355MC(2) and Docol 800HHE. For the rest of the materials, HTT results are not so distinctly low when compared to other test results. DBT and Diabolo tests create the highest combination of major (tensile) and minor (compressive) strain in general, with S700MC(1) being the only material that creates a rather uniform scatter and results for all tests. The result pattern in 2D Edge FLD shows the level where the combination of major and minor strain become limiting. It can be presumed that forming beneath this level should create crack-free components on the edge areas. This approach creates a good visualization of the qualities of the different materials when comparing overall edge ductility.

![Figure 4. “2D Edge FLD” for studied steels: (a-c) 355 MPa and (d-f) 700MPa level.](image-url)
2D Edge FLD approach could be too conservative in some cases. For example, in a situation that S355MC(1) or S700MC(1) materials are formed with specific NHE test loading situation. In this case, the limiting curve would be considerably lower than the results of NHE test indicate, as seen in Figure 4(b) and (d). If part design includes only one specific loading case, materials could be optimally tested only by one test to describe edge ductility. However, industrial parts often include multiple different loading cases, creating the need of simultaneous judgement of different stress-strain situations. This will make it very difficult or even impossible to choose only one test to describe edge ductility in a proper way. In order to complement the approach of major and minor strain, it is important to take the complete strain state situation into consideration, including thinning tendency and strain path.

3.3. 3D Edge FLD

Going even further with analysis, an attempt was made to describe the final situation just before crack formation, including thinning as thickness reduction strain component $\varepsilon_1$. Results are presented as “3D Edge FLD” surface plots for 355 MPa and 700 MPa materials in Figure 5 and Figure 6, respectively. The 2D Edge FLD has now been placed into the Y- and X-axes, including the maximum local strain before cracking for the $\varepsilon_3$ and $\varepsilon_2$ components. The thickness reduction strain, $\varepsilon_1$, is in the Z-axis, creating the “height” of the surface. The idea is to visualize the limiting strains, not only for the major and minor strains but also for the maximum thinning before crack occurs. As can be seen in Figure 5, steel S355J2 creates a much lower and smaller limiting surface than the two other 355 MPa steels, indicating that the material does not exhibit much necking of the edge before cracking. Therefore, it can be said that the material is very prone to edge cracking but without the propensity to necking. With the “3D Edge FLD” approach, it is also possible to evaluate the thinning tendency in more detail. With similar levels of major and minor strain, a very different level of thinning of the edge area is seen for different materials. For example, with rather high minor and major strain levels, the Docol 800HHE material creates more thinning than the other two 700 MPa grades. It is also evident that when comparing the two 700 MPa grades, standard S700MC(1) and Docol 800HHE, the overall “edge ductility surface” is much wider and higher for the latter one. It can be concluded that the amount of necking on the edge area can be very different from test to test and from material to material.

![Figure 5. “3D Edge FLD” for 355 MPa materials.](image)

![Figure 6. “3D Edge FLD” for 700 MPa steels.](image)
There are often limits for the maximum thinning of a material when it comes to part production and simulations. According to these results, it could be stated that the thinning limit, when edge cracking is used as a failure criterion, could be very different in different materials. For example, a 0.2 [log] thickness strain could be too much for some materials, while for others, it would be underestimating the material ability. This could lead to a situation where full material performance is not utilized if the thinning of the edge does not reach critical limits. When comparing different materials, 3D Edge FLD visualizes and describes the overall edge ductility in a comprehensive way and makes the comparison between materials easy. This would also allow for more information during the steel development phase when comparing different steel concepts.

3.4. Simulation case

The simulation case was run with the Autoform R10 forming simulation software for the S700MC(1) steel. Two hypothetical parts were designed to create good and bad situation in the edge forming area. The aim is to present simplified example on how Edge FLD could be used for cracking risk evaluation. The schematic presentation of the parts production process for both good and intentionally bad design is shown in Figure 7. Blanks (500mm x 450mm) are initially cut into similar shape followed by a drawing operation (depth of 100mm), trim cutting and flanging operation. It can be noted that there is a risk of increased cut edge strain in the concave area of the part. Hence, it is important to be careful with the trim line in this area. For the good design, the trim line in the cutting operation is smooth and has no clear localization points. Whereas for the bad design, a cut-out is intentionally added right into the concave area (arrow) to act as a localization point for the strains in the following flanging operation. The more intensive localization behavior of the bad design can be clearly seen in Figure 7(c), showing major strain concentration along the edge in the critical area.

![Figure 7. Part production phases for (a-a''') good and (b-b''') bad design together with (c) strain concentration along the critical area.](image)

Strains are simulated on the critical area for all three strain components and presented in 2D Edge FLD in Figure 8a. It can be concluded that the part with good design could be possible to produce with S700MC(1) as it is just on the forming limit curve of the 2D Edge FLD. On the other hand, the part with bad design creates a major-minor strain combination which is in the crack risk area above the forming limit curve in the 2D Edge FLD, leading to a high risk of crack formation in the forming process. Thickness reduction was also analyzed in the simulation process. The results for both the good and bad design are put into 3D Edge FLD in Figure 8b. It can be seen that the good design (green dot) is located below the limiting strain surface while the bad design (black dot) creates strain combination above the strain surface. This indicates that the thickness reduction might also be too much for the bad design, leading to problems in part production.
In this study, the limiting strain was determined as maximum local strain just before cracking from the very edge of the samples. Atzema et al. [10] indicated that this approach can be feasible to describe limiting failure criteria for edges and could be utilized for edge strain criteria for simulation purposes. However, there is a possibility that this approach could create too optimistic an expression of failure criteria in real industrial applications. Therefore, fine-tuning of failure criteria should be performed through validation tests in the future. One possibility could be to use a similar best-fit parabola process that is used for FLD determination [15], which is an approach based on necking behavior. This approach could lead to better scatter behavior control, as the cracking phenomenon itself tends to be a more or less random event, especially in sheared edges. However, as seen from the results, the necking phenomenon could be suppressed in certain situations and may be difficult to use for edge cracking. In future work, proper limiting strain criteria needs to be validated through modeling and actual verification tests for edge areas.

3.5. Strain path

In order to identify the characteristic loading of each case, strain paths for different test setups are shown in Figure 9 for S355J2 and Docol 800HHE. These materials were selected to describe the low and high end of studied materials, from the perspective of both the strength as well as edge ductility. One representative test was selected for each case, and the strain history was plotted for each frame for the major $\varepsilon_3$ and minor $\varepsilon_2$ strains. It can be seen that the strain path is rather linear in all cases, taking into account that in most cases there seems to be some scatter in the final, unstable region before fracture. For S355J2, the path seems to slightly curve toward the plane strain region at the end stages of the DBT and Nakajima tests, indicating that the compressive minor strain slightly decreases. The same behavior was not seen for the Docol 800HHE material, and strain paths follow a linear path. This indicates that the strain paths can also be affected by the material properties, not only by test geometry. The effect of linear vs. non-linear strain path during edge forming could be an interesting research field in the future, together with different pre-strain conditions.

Figure 8. Maximum strains in simulation vs (a) 2D Edge FLD and (b) 3D Edge FLD.

Figure 9. Strain path for (a) S355J2 and (b) Docol 800HHE in each test for major and minor strain.
4. Summary
In this study, several known edge ductility tests were selected to study the varying loading cases of sheared edges. Results are presented in multiple different ways: maximum local major strains, 2D Edge FLD and 3D Edge FLD, including presentation of the strain path in different test setups. According to the results, relying only on one test method can lead to erroneous choices during steel development or when selecting material for specific applications. Therefore, multiple different test methods are needed in order to describe material edge ductility in a comprehensive way. Approaches with 2D and 3D Edge FLDs were presented, and they created a good visualization of overall edge ductility, providing more information about material behavior in different tests. It is shown that Edge FLDs could be used to evaluate limiting strains also for simulation purposes. More work needs to be done to set and validate the limiting failure criteria for sheared edges in different loading situations.

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