Local formability of AHSS: Measurement technique, specimen types and robustness

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Abstract. The recently proposed classification scheme for AHSS with global and local formability enables a material specific process development, allows a designation based on mechanical properties, as well as an assessment of various properties: deep drawability, edge-crack sensitivity, bendability, damage tolerance and fracture toughness. Local formability is measured by local fracture strains, e.g. area reduction at fracture or true thickness strain at fracture. Based on investigations of AHSS with strengths between 600 and 1000 MPa from different steel suppliers, this contribution addresses the influence of the measurement technique, of different specimen types and different sheet thicknesses on the measure for local formability. Furthermore, the correlation between true thickness strain at fracture and hole expansion ratio and also the hardness difference of the microstructure, as well as no correlation between local formability and bending angle according to VDA 238-100 are confirmed. It is shown that the influence of the measurement technique for true thickness strain at fracture is negligible regarding the differentiation between the investigated grades. Using “uniaxial” tensile tests with specimen types 2 and 3 according to ISO 6892-1 one can obtain similar local fracture strains. Same states for the notched tensile tests with radii of 4 mm and 5 mm. The values gained by the smaller A30 mm specimen show slightly lower values compared to the “uniaxial” tensile specimen types. With increasing sheet thickness, a slight decrease in true thickness strain at fracture resulting from the combination of a changing width-to-thickness ratio of the tensile specimen and different microstructures can be seen. The large range of the measure for local formability using materials from different suppliers and different sheet thicknesses motivates the definition of requirements for material specifications and source approvals.

1. Introduction
Advanced high strength steels (AHSS) are widely used in modern car-body manufacture for reaching lightweight design and for increasing passive safety. Accompanied by their higher strength, AHSS sheets display a complex and challenging forming behavior compared to mild steels or high-strength low alloyed steels. Dual-phase (DP) steels show high global formability. However, their low local formability can lead to failure in the production process because of damage evolution leading to part fracture at tight radii or edge-cracks [1]. Complex-phase (CP) steels with their homogeneous bainitic/martensitic microstructure exhibit a high local and poor global formability, which makes them most suitable for bending processes with high local strains (e.g. roll forming). To decipher the complex
forming behavior of AHSS, Hance and Davenport [2] introduced a global and local formability scheme to classify and differ nine AHSS with a tensile strength of 1000 MPa. Heibel et al. [1] linked this scheme and the property of local formability to damage tolerance, edge-crack sensitivity, fracture toughness and bendability of high strength multiphase steels.

2. Global and local formability

According to [1], global formability is the ability of a material to undergo plastic deformation without formation of a localized neck respectively to distribute strains uniformly. In contrast, local formability is the ability of a material to undergo plastic deformation in a local area without fracture. As a measure for global formability the true uniform strain \( \varepsilon_u \) measured via uniaxial tensile testing is commonly used [1, 2 and 3]. Heibel et al. [1] showed a positive correlation of \( \varepsilon_u \) with the minimum of the forming limit curve and the drawing depth of a cross die geometry for AHSS in the range between 600 and 1000 MPa. Local formability is measured via thickness or area reduction of a fractured uniaxial tensile specimen. Hance and Davenport [2] used true fracture strain \( (TFS = \ln(A_0/A_f)) \), Larour et al. [3] applied the reduction of cross section area at fracture \((Z = (A_0 - A_f)/A_0)\) and Heibel et al. [1] used only the thickness information by means of true thickness strain at fracture \((\varepsilon_{3f} = \ln(t_0/t_f))\). With all these measures for local formability, the edge-crack sensitivity of AHSS can be assessed. A positive correlation between \( Z \) [3] and \( \varepsilon_{3f} \) [1] with the hole expansion ratio HER of punched specimens has been found. Westhäuser et al. showed this correlation for local strains measured via digital image correlation and the HER of milled specimens. In the work of Wagner et al. [5] and Heibel et al. [6] notched tensile tests have been conducted to evaluate local formability and damage tolerance as well as to create fracture limits of AHSS. In [7] Wagner and Larour investigated the thickness and thus stress state dependency of several measures for local formability with several specimens. They discovered that the geometry of the specimen might have an influence on local strain measurements and that specimens showing shear fracture gain the most stable results.

3. Materials and methods

This work addressed the measurement technique, the influence of different specimen types on the measure of local formability, the influence of sheet thickness (between 0.80 mm and 3.00 mm) as well as the influence of four different suppliers (abbreviated by A, B, C and D). The investigations are based on cold rolled (CR) steels DP600, DP800 and CP1000. All 58 tested materials fulfil the requirements specified in VDA 239-100 (see table 1).

Table 1. Range of mechanical properties according to VDA 239-100

|       | Yield strength | Tensile strength | Total elongation | n-value |
|-------|----------------|------------------|------------------|---------|
|       | \( R_{0.2} \) in MPa | \( R_m \) in MPa | \( A_{80 \text{ mm}} \) in % | \( A_{50 \text{ mm}} \) in % | \( n_{10-20/Ag} \) |
| DP600 (CR330Y590T-DP) | 330 - 430 | 590 - 700 | 20 | 21 | 0.14 |
| DP800 (CR440Y780T-DP) | 440 - 550 | 780 - 900 | 14 | 15 | 0.11 |
| CP1000 (CR780Y980T-CP) | 780 - 950 | 980 - 1140 | 6 | 7 | - |

Every material is tested with the uniaxial tensile tests according to ISO 6892-1, specimen type 2 \((A_{80 \text{ mm}}, \text{width 20 mm})\). Some materials are also tested with uniaxial tensile tests according to ISO 6892-1 with different specimen types: type 3 \((A_{50 \text{ mm}}, \text{width 25 mm})\), a smaller uniaxial tensile specimen \((A_{30 \text{ mm}}, \text{width 5 mm})\), and two notched tensile test specimens \((R_{4 \text{ mm}} \text{ and } R_{5 \text{ mm}}, \text{see figure 1})\). Furthermore, bending tests according to VDA 238-100, hole expansion tests according to ISO 16630 and micro hardness measurements (procedure detailed in [1]) are conducted. In order to accomplish statistical requirements 5 specimens have been tested for each test condition. Hole expansion trials have been performed 30 times.
For the calculation of $\varepsilon_{3f}$, $t_f$ is measured with a light microscope at the thinnest location of the fracture surface as depicted in [1]. $\bar{\varepsilon}_{3f}$ is calculated with $\bar{t}_f$ as proposed by [2] ($\bar{t}_f = \frac{1}{6} \cdot (t_{left} + 4t_{middle} + t_{right})$). The thickness measurement is shown exemplarily in figure 2.

$$R_{4 \text{mm}}$$

$k$  

$R_{5 \text{mm}}$

![Figure 1. Notched specimens R$4 \text{mm}$ and R$5 \text{mm}$](image)

![Figure 2. Examples of thickness measurement location of investigated specimen types](image)

4. Results
The two methods to calculate the true thickness strain at fracture are compared in figure 3 (test direction longitudinal to rolling direction, LD) and figure 4 (test direction transversal to rolling direction, TD) based on all measured specimens. The conclusions for both testing directions are similar: very high correlation between both methods, indicated by the very high $R^2$ values, and very low scatter (0.04 on average). The values of $\varepsilon_{3f}$ gained by measuring only the thinnest position of the fracture surface are on average 0.14 higher than the results for $\bar{\varepsilon}_{3f}$, which need the thickness to be measured at 3 defined positions (left, middle and right of the fractured surface). The differentiation between the materials is the same.

Hence, the further results are presented by means of $\varepsilon_{3f}$ measured in specimens tested longitudinal to rolling direction.

![Figure 3. $\varepsilon_{3f} - \bar{\varepsilon}_{3f}$ (LD)](image)

![Figure 4. $\varepsilon_{3f} - \bar{\varepsilon}_{3f}$ (TD)](image)
Table 2 details the influence of different specimen types and thus different stress states. The uniaxial tensile test according to ISO 6892-1 specimen type 2 (A\textsubscript{80 \text{mm}}) is taken as reference and set to 100%. The wider A\textsubscript{50 \text{mm}} specimens yield quite similar results. The \(\varepsilon_3f\) values gained by the smaller A\textsubscript{30 \text{mm}} specimen are lower. This specimen displays the lowest width-to-thickness ratio of the uniaxial tensile test specimens. The measured values of \(\varepsilon_3f\) are quite similar for both the R\textsubscript{4 \text{mm}} and R\textsubscript{5 \text{mm}} specimens. They are on the same level as the values gained by both the A\textsubscript{80 \text{mm}} and A\textsubscript{50 \text{mm}} specimens for materials exhibiting a high local formability (\(\varepsilon_3f > 1.00\)). Materials showing a lower local formability seem to be more influenced by the plane-strain stress state. As can be seen in figure 2, finding the minimum thickness and the following measurement is the easiest using the R\textsubscript{4 \text{mm}} specimen. Nevertheless, the A\textsubscript{80 \text{mm}} specimen is used for further investigations, as this specimen allows the measurement of both global and local formability.

**Table 2. Influence of specimen type on \(\varepsilon_3f\)**

| Specimen Type | \(\varepsilon_3f\) | A\textsubscript{80 \text{mm}} | A\textsubscript{30 \text{mm}} | A\textsubscript{50 \text{mm}} | R\textsubscript{4 \text{mm}} | R\textsubscript{5 \text{mm}} |
|---------------|---------------------|-------------------------------|-------------------------------|-------------------------------|---------------------|---------------------|
| DP600 1.00 mm (A) | 1.05                | 100 %                         | 85 %                          | 96 %                          | 91 %                | 96 %                |
| DP600 1.50 mm (D) | 1.07                | 100 %                         | 99 %                          | 108 %                         | 107 %               | 106 %               |
| DP800 1.00 mm (D) | 0.79                | 100 %                         | 94 %                          | 101 %                         | 88 %                | 85 %                |
| DP800 1.50 mm (D) | 0.76                | 100 %                         | 71 %                          | 98 %                          | 82 %                | 84 %                |
| CP1000 1.00 mm (A) | 1.23                | 100 %                         | 101 %                         | 100 %                         | 105 %               | 98 %                |
| CP1000 1.50 mm (A) | 1.16                | 100 %                         | 91 %                          | 104 %                         | 111 %               | 110 %               |
| Mean value     |                     | 100 %                         | 90 %                          | 101 %                         | 97 %                | 96 %                |

Figure 5 confirms the positive correlation between the true thickness strain at fracture and the hole expansion ratio (HER) found in former research. HER values are determined according to ISO 16630. Thus, \(\varepsilon_3f\) allows to assess the edge-crack sensitivity, a special case of fracture toughness. Another observation is the considerably lower scatter of the true thickness strain at fracture compared to the hole expansion ratio for steels exhibiting a higher local formability.

![Figure 5. \(\varepsilon_3f\) – HER (LD)](image)

In contrast, no correlation is found between \(\varepsilon_3f\) and the bending angle according to VDA 238-100 (figure 6). As outlined in [1], this does not mean that \(\varepsilon_3f\) is not suitable to assess bendability. On the
contrary, the bending angle itself is not a proper measure for the bendability of high strength multiphase steel sheets \[1\].

Wagner and Larour \[7\] reported a possible dependency of \(\varepsilon_{3f}\) on the sheet thickness for materials produced by one supplier. This can be partly endorsed with figure 7. DP600 and DP800 steels of supplier A display a decrease in \(\varepsilon_{3f}\) with increasing sheet thickness. CP1000 materials from this supplier show a quite constant local formability, whereas the CP1000 materials produced by supplier B exhibit a slight decrease in \(\varepsilon_{3f}\) with increasing sheet thickness. All DP800 materials show lower true thickness strains at fracture for higher sheet thicknesses. In contrast to the DP600 materials of supplier A, DP600 materials produced by D stay above 1.00 even for higher thicknesses. It should be mentioned, that the scatter at least for DP600 in 1.75 mm, 2.00 mm and 2.50 mm from supplier D is quite high. Two different coils from supplier A have been tested for every sheet thickness. The maximum difference is obtained for DP600 in 1.50 mm with \(\varepsilon_{3f}\) of 1.06 and 0.74. DP800 in 1.20 mm shows a maximum of \(\varepsilon_{3f}\) with 1.03 and a decrease of 0.14 for the second coil. The two values measured for CP1000 with 2.10 mm are 1.20 and 1.06. In general, the difference between two coils is higher than the standard error for 5 tested specimens of one coil.

The global and local formability scheme in figure 8 gives an overview of the measured ranges for the three investigated steels. For CP1000, the true thickness strain at fracture varies from 0.90 to 1.24, for DP800 from 0.36 to 1.05 and for DP600 from 0.65 to 1.17. As expected, global formability for
CP1000 is low with true uniform strain $\varepsilon_u$ from 0.04 to 0.05. DP800 reaches values from 0.09 to 0.14. DP600 exhibits the highest global formability. True uniform strains lie in a range from 0.13 to 0.15.

Figure 8. Global-local formability scheme

The high range for $\varepsilon_{3f}$ as a measure for local formability is a challenge for the automotive industry as it leads directly to an uncertainty about the robustness of the production process (e.g. occurrence of edge cracks). Also, the crash dimensioning can be improved when taking this information on local formability into account.

Requirements for local formability have yet not been defined in any specification. According to Heibel et al. [1], local formability depends on microstructural characteristics, especially the sensitivity to a material’s damage evolution. Specifications like VDA 239-100 define microstructural characteristics in a very general way: “The grain size shall be consistent throughout the thickness of the sheet so that they do not interfere with the part properties.”, and “Occurrence and type of material inhomogeneities (e.g. martensite lines, slag inclusions, segregations) should represent the state-of-the-art technology and should be limited in order not to affect the cold forming properties.” The main driver of damage evolution is the microstructural heterogeneity and the hardness difference between the phases [1].

Figure 9 depicts the correlation between $\varepsilon_{3f}$ and the micro hardness difference $\Delta$HV for some materials. Nital-etched micrographs of DP800 materials with highest and lowest local formability are shown in figure 10. The DP800 material with the highest local formability displays a homogeneous microstructure with small ferrite grains and finely dispersed martensite particles without prone martensite lines. The hardness difference between the phases is low with 241 HV (cf. [1]). The DP800 material with the lowest local formability shows high hardness difference (509 HV) and strong microstructural heterogeneity. The size of the ferrite grains is between 5 and 10 $\mu$m and martensite particles are mainly arranged in lines, which leads to a low damage tolerance and high edge-crack sensitivity. As this is also the DP800 material with the highest sheet thickness of 3.00 mm it can be concluded, that $\varepsilon_{3f}$ is influenced by both, the stress state and the microstructure. The impact of the latter seems to be bigger, as the CP1000 materials and DP600 materials from supplier D show values that are nearly independent from thickness. As can be seen in figure 7, the local formability of the CP1000 materials produced by supplier B is constantly lower than the local formability of CP1000 materials from supplier A.
Figure 10 further shows the related microstructures. CP1000 from A displays a homogenous bainitic/martensitic microstructure with a low hardness difference—a typical CP steel. Contrarily, CP1000 from B shows a different material concept. With small ferrite grains and a high amount of finely dispersed, hard martensite this material could be also classified as a DP-steel with a high yield strength.

Figure 9. $\varepsilon_{3f} - \Delta HV$ (LD)

Figure 10. Nital-etched micrographs
5. Conclusion

Based on investigations of DP600, DP800 and CP1000 from different steel suppliers this contribution addresses the influence of the measurement technique of different specimen types and different sheet thicknesses on the measure for local formability. Furthermore, the correlation between true thickness strain at fracture and hole expansion ratio and also the hardness difference of the microstructure, as well as no correlation between local formability and bending angle according to VDA 238-100 are confirmed. It is shown that the influence of the measurement technique for true thickness strain at fracture is neglectable regarding the differentiation between the investigated grades. Using “uniaxial” tensile tests with specimen types 2 and 3 according to ISO 6892-1 one can obtain similar local fracture strains. Same states for the notched tensile tests with radii of 4 mm and 5 mm. The values gained by the smaller A_30 mm specimen show slightly lower values compared to the “uniaxial” tensile specimen types. With increasing sheet thickness, a slight decrease in true thickness strain at fracture resulting from the combination of a changing width-to-thickness ratio of the tensile specimen and different microstructures can be seen. The large range of the measure for local formability using materials from different suppliers and different sheet thicknesses motivates the definition of requirements for material specifications and source approvals.

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