Investigation on local ductility of 6xxx-aluminium sheet alloys

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Abstract. Within the scope of this paper influence of localization of loading conditions on the ductility of two different 6xxx-aluminium sheet alloys is investigated. In order to improve the prediction of sheet material crash performance, material parameters based on uniaxial tensile and notched tensile tests are determined with varying consolidation areas. Especially evaluation methods based on the localized necking behaviour in tensile tests are investigated. The potential of local ductility characterisation is validated with results of Edge-Compression Tests (ECT) which applies load conditions that occur in actual crash events.

1. Introduction
In order to satisfy continuously increasing legal regulations, further improvement of crash performance proves to be one of the major technological challenges of modern automotive engineering [1]. As simultaneously the interest in lightweight construction increases, it is crucial to have detailed specifications of material properties available to ensure maximal potential in car body design. Most of the well-established material testing methods (e.g. tensile test) were invented to ensure producibility and therefore investigate material behaviour at planar loading cases that are emerging in metal forming processes. The prediction of crash performance based on these material parameters is limited [2] as the loading conditions occurring during various crash scenarios can be three dimensional and happen to be limited to a relative local area of the structural body parts.

Current method to evaluate crashworthiness of sheet material is the axial crush test of closed hat sections, which was inspired by the component testing of crash-boxes [3–4]. With the Edge Compression Test (ECT) that was presented in [5] the crash-relevant loading conditions from axial crushing of a closed hat section are transferred to a laboratory test setup which allows quantification and differentiation of sheet material crashworthiness [5].

In the experimental study presented in this paper another approach to characterize crashworthiness of two different 6xxx-aluminium sheet alloys with given testing procedures is investigated. Ductility is therefore evaluated based on analysis of tensile and notched tensile tests with varying consolidation areas. Potential of local ductility characterisation is validated with results of ECT.

As 6xxx-series aluminium exhibit only slight sensitivity to high strain rates at room temperature [6] all experimental investigations are examined with quasistatic loads.

2. Materials investigated

2.1. Chemical composition
The investigated materials in this study are 6xxx-series aluminium sheet alloys with 1.7 mm nominal thickness. Table 1 shows the chemical composition of the alloys. Although the composition is similar in most of the elements, reduced silicon and increased magnesium content is detected for the EN AW 6xxx-C alloy.
### TABLE 1. Chemical composition of the test materials.

| Material        | Si [wt%] | Fe [wt%] | Cu [wt%] | Mn [wt%] | Mg [wt%] | Cr [wt%] | Zn [wt%] | Ti [wt%] |
|----------------|----------|----------|----------|----------|----------|----------|----------|----------|
| EN AW-6xxx     | 1.060    | 0.239    | 0.066    | 0.161    | 0.469    | 0.015    | 0.013    | 0.020    |
| EN AW-6xxx C   | 0.556    | 0.180    | 0.071    | 0.136    | 0.636    | 0.012    | 0.007    | 0.017    |

2.2. Mechanical properties

To characterise the mechanical properties of mentioned material, uniaxial tensile tests were carried out with various orientations to rolling direction. Before testing the specimens were heat treated for 20 minutes at 185°C in an experimental oven to obtain T6 conditions. The resulting mechanical properties obtained after heat treatment are displayed in table 2. Minimum for uniform and fracture elongation occurs with tension in rolling direction for both alloys. As there are only slight deviations for the tested orientations, following examinations in this paper are only carried out in rolling direction as this orientation shows minimal ductility.

### TABLE 2. Mechanical properties of the test materials gained by tensile tests.

| Material          | Heat treatment condition | Rolling dir. [°] | Yield Str. RP0,2 [MPa] | UTS Rp0,2 [MPa] | Uni. elon. A g [%] | Frac. elon. A80 [%] | r-value r [-] |
|-------------------|--------------------------|-----------------|------------------------|-----------------|-------------------|-------------------|---------------|
| EN AW-6xxx        | T6                       | 0               | 169.0                  | 271.3           | 19.2              | 24.4              | 0.7           |
| EN AW-6xxx C      | T6                       | 45              | 161.0                  | 265.0           | 20.6              | 25.6              | 0.4           |
|                   | T6                       | 90              | 157.7                  | 264.0           | 19.5              | 24.3              | 0.8           |
|                   | T6                       | 0               | 173.2                  | 259.3           | 16.0              | 20.1              | 0.8           |
|                   | T6                       | 45              | 167.1                  | 254.4           | 18.1              | 21.6              | 0.4           |
|                   | T6                       | 90              | 171.0                  | 255.6           | 16.1              | 20.4              | 0.9           |

In case of such uniaxial loading condition increased ductility is determined for EN AW-6xxx alloy considering uniform and fracture elongation. This conflicts with the general expectations of EN AW-6xxx C having increased ductility and demonstrates the limited potential of crashworthiness prediction when using solely uniaxial testing methods.

2.3. Crash performance based on Edge Compression Test (ECT)

Current method to evaluate crashworthiness of sheet material is the axial crush test which is derived from component testing rather than pure material testing and only allows qualitative ductility characterization. In [5] edge compression test was established as a simplification of axial crush test as only the critical area is investigated. The entire specimen is accessible for optical inspection at every step of the procedure and therefore, in addition to the visual evaluation of ductility, in situ strain measurement can be applied. The 6xxx-aluminium alloys that were used in [5] to carry out ECT are equal to the alloys used in this paper. While EN AW-6xxx C tolerated the emerging loads, EN AW-6xxx specimens showed fracture at the area of the bendline (figure 1). Ductility for EN AW-6xxx C was evaluated superior to EN AW-6xxx with a maximum of 36 % according to strain measurement.

FIGURE 1. (a) In-situ strain measurement of ECT for EN AW-6xxx and EN AW-6xxx C alloy [5]
3. Investigation on localization of loading

3.1. Tensile test
As stated before uniaxial tensile tests investigate material behaviour at planar loading cases and thus cannot predict crash performance of materials adequately if evaluated according to the standardised method. Nevertheless it is possible to analyse material ductility at combined loading conditions if the evaluation is focussed on the post-necking behaviour, as the emerging loading conditions in this phase happen to be three-dimensional in the area of necking.

3.1.1. Influence of localized necking
Figure 2 (a) shows the stress-strain-curves of both investigated alloys gained by uniaxial tensile tests. Strain measurement is realized by mechanical extensometer with standardised gauge length of 80 mm according to DIN EN ISO 6892-1. The stress-strain-curves show increased fracture elongation for the EN AW-6xxx alloy. As the EN AW-6xxx C is proved to show increased ductility, the results demonstrates the poor potential of the tensile test for predicting crashworthiness if evaluated according to DIN EN ISO 6892-1. The potential of characterising material ductility based on the necking behaviour has been investigated numerous times. Various ductility criteria have been developed to describe the necking behaviour in scalar values. In addition to strain based criteria such as the relation of fracture elongation and uniform elongation ($\Delta A_{\text{abs}}$ and $\Delta A_{\text{Spec}}$) [7] there are stress based criteria (e.g. relation of ultimate tensile strength to fracture stress ($\varepsilon_{\text{postuni}}$) and $\Delta R/R$ [9]) as well as combined criteria ($CFS$ [10] and $DV_{\text{postuni}}$[8]) and combinations of the aforementioned. Figure 2 (b) presents various advanced evaluation methods. All results of these necking evaluation methods improve the ductility prediction. The great potential of focussing on the post critical phase of the forming process is obvious.

![Stress-strain-curve](a)

虽然应力基函数能够预测EN AW-6xxx C合金的改进的碰撞防护能力，但这些函数的使用受到很大影响，因为断裂应力的下降在测试的最后几秒钟的极短时间中很大。由于局部颈缘和三维加载条件的产生，因此考虑到局部颈缘的评价更加保守，但总体上更加可靠，因为分散度大大降低。

3.1.2. Influence of consolidation area
As stated before evaluation of the necking zone improves the potential of predicting alloy crashworthiness with tensile tests by far. Since the necking zone is only a small area of the whole specimen, strain evaluation with mechanical extensometer with standardised gauge length of 80 mm...
cannot be sensitive to local strain behaviour in necking zone. Therefore reduction of gauge length especially due to the change of measurement technique to optical evaluation has high potential of increasing sensitivity of ductility characterisation by strain evaluation of necking zone in tensile tests. The tensile tests are therefore evaluated using optical measuring system GOM Aramis 5M. Great advantage of this approach is the variation possibility of consolidation area subsequent to testing. Figure 3 (a) displays the optical evaluation method with different consolidation areas. As shown in Figure 3 (b), the reduction of consolidation area results in the increase of fracture strain for both alloys while uniform elongation stays at similar values as elongation at beginning of localized necking is consistent in all areas of the specimen. It can be seen, that in contrast to the global elongation values with large consolidation areas, local elongation values with small consolidation areas (< 1 mm) are potent in predicting the superior ductility of EN AW-6xxx C alloy. Based on this evaluation method of reducing consolidation area to put focus on the area of localized necking a ductility characterization to estimate crashworthiness of aluminium alloys is possible.

![Figure 3](image-url)

**FIGURE 3.** (a) Stress-strain curve gained by uniaxial tensile tests of investigated materials; (b) Influence of consolidation area size on uniform and fracture strain in uniaxial tensile test

### 3.2. Notched Tensile Test

The possibility of using localized, combined loading conditions to characterize aluminium sheet alloys crashworthiness has been displayed with the analysis of the necking area of uniaxial tensile tests. As the relevant loading conditions are only a small part of the tensile test and can therefore only be utilized with advanced evaluation methods, additional approaches for ductility characterization are to be investigated.

As localized, combined loading conditions can be gained by using the stress concentration occurring at tensile loading on sharp notches, notched tensile tests with two different notch radii \(r = 1\) mm, \(r = 4\) mm are investigated within the scope of this study. The specimen geometries are displayed in figure 4 (a). As shown the gauge length for regular elongation measurement is given with \(L_0 = 15\) mm for both of the geometries. As deformation occurs only within the notched area of specimen, the measured elongation \(L_1\) is referred to the initial notch length \((l_{0,1}) = 2\) mm respectively \((l_{0,4}) = 8\) mm) to gain the characteristic strain \(\varepsilon_{NT,C}\) (equation (1)). The associated stress \(S_{NT}\) represents the quotient of measured force \(F_{NT}\) and the cross-sectional area at the centre of the notches with minimal width of \(b_{NT} = 4\) mm and the initial sheet thickness \(s_0 = 1.7\) mm (equation (2)).

\[
\varepsilon_{NT,C} = \frac{L_1 - L_0}{L_0} \quad (1)
\]

\[
S_{NT} = \frac{F_{NT}}{b_{NT}s_0} \quad (2)
\]
FIGURE 4. (a) Specimen geometries used in this study: (1) Notched tensile specimen with notch radius $r = 1 \text{ mm}$ (2) Notched tensile specimen with notch radius $r = 4 \text{ mm}$ (3) Standardized a80 tensile specimen; (b) Stress-strain-curves gained by notched tensile tests

The resulting stress-strain behaviour is displayed in figure 4 (b). All stress-strain curves show a linear section, showing elastic deformation, followed by plastic deformation areas with a characteristic stress maximum ($R_m$). Compared to stress-strain curves from uniaxial tensile tests (e.g. figure 2 (a)) the emerging stress and strain drop in post-critical section after reaching maximal stress is relatively high. While the stress-strain-curves for notch radius $r = 4 \text{ mm}$ are similar for both tested alloys, EN AW-6xxx C alloy shows significant increased maximum strain before fracture compared to EN AW-6xxx alloy for notch radius $r = 1 \text{ mm}$. This indicates the increased potential for ductility characterization with sharp notched specimen geometry.

3.2.1. Evaluation of post-critical section

To investigate further potential of notched tensile tests, post-critical section of stress-strain curves are investigated according to the evaluation of necking in tensile tests. Results of various ductility criteria from uniaxial tensile evaluation are displayed in Figure 5 (a). It can be seen, that stress based criteria ($\varepsilon_{\text{postuni}}$ and $\Delta R/R$) as well as combined criteria ($\text{CFS}$ and $D\varepsilon_{\text{postuni}}$) indicate almost equal ductility for the tested alloys. The results show slightly increased values for EN AW-6xxx C alloy with notch radius $r = 4 \text{ mm}$ and even superior ductility for EN AW-6xxx alloy with notch radius $r = 1 \text{ mm}$.

FIGURE 5. (a) Ductility criteria based on stress/strain behaviour of notched tensile tests; (b) Stress/strain values gained by notched tensile tests for advanced ductility evaluation
In contrast strain based ductility criteria ($\Delta A_{\text{abs}}$ and $\Delta A_{\text{Spec}}$) show high potential of describing superior ductility of EN AW-6xxx C alloy especially for the specimens with notch radius $r = 1$ mm. This is due to the fact, that considered fracture strain $A_f$ is highly increased for EN AW-6xxx C alloy with notch radius $r = 1$ mm while the “uniform strain” $A_g$ at maximum of stress is similar for both alloys. Opposite to this no significant differences can be observed in stress values ($R_m$ and $R_f$) for both alloys and notch radii. Figure 5 (b) summarises the considered stress/strain values for ductility evaluation.

3.2.2. Influence of consolidation area

The carried out investigations on notched tensile tests show high potential of crashworthiness characterization and differentiation between the tested aluminum alloys as the loading conditions are combined and localized due to the notch effect. To analyze the effect of load and strain localization, evaluation of notched tensile tests with reduced sizes of consolidation area is realized based on optical measurement. In addition to initial gauge length ($L_0=15$ mm) consolidation areas of 1 mm and single point evaluation are investigated with both notch radii as depicted in figure 6 (a). Single point evaluation is carried out at the point with maximal equivalent strain before fracture. As the maximum of stress concentration occurs at the notch radius, the investigated point is located at apex of the notch. Influence of consolidation area size on uniform strain $A_g$ and fracture strain $A_f$ gained by notched tensile tests with notch radii $r = 1$ mm and $r = 4$ mm for both investigated alloys is displayed in figure 6 (b). It can be seen, that reduction of consolidation area size leads to increased fracture strains while uniform strain values are relatively equal for all consolidation areas. For notch radius $r = 4$ mm, increase of fracture strain is highest for EN AW-6xxx C alloy and therefore allows prediction of increased ductility compared to EN AW-6xxx alloy at small consideration areas (< 1 mm). This effect is similar to uniaxial tensile test as the smooth notch radius $r = 4$ mm leads to strain distribution in the relatively large notch area. With increasing distance to the apex of the notch, the occurring load condition is less critical and the strain portions in this area can therefore not be used for differentiating the alloys ductility. If the consolidation area is reduced to the critical area at the apex of the notch (< 1 mm) the ineffective proportions of the strain are eliminated and therefore the potential of ductility characterization is increased.

In contrast to that the relation between the investigated alloys is consistent with all consolidation areas for notch radius $r = 1$ mm, indicating no significant increase of potential for ductility differentiation due to reduced consolidation size. This can be attributed to the sharp notch radius which allows no spread in strain distribution and therefore predicts increased ductility even without localized evaluation as all occurring strain is localized in the critical area around the apex of the notch and can therefore be used for ductility differentiation.

![FIGURE 6. (a) Investigated consolidation areas used for optical evaluation of notched tensile tests, (b) Influence of the size of consolidation area on resulting strain values gained by notched tensile tests](image-url)
3.3 Comparison between uniaxial tensile test and notched tensile test

To compare the ductility evaluation with uniaxial tensile tests to the results from notched tensile tests with different notch radii the quotients $Q_{abs}$ and $Q_{spez}$ are established to determine the relative ductility of EN AW-6xxx C alloy compared to EN AW-6xxx alloy. The results for strain based ductility criteria $\Delta A_{abs}$ and $\Delta A_{spez}$ are therefore related according to equation (3) respectively equation (4).

$$Q_{abs} = \frac{\Delta A_{abs} (EN\ AW–6xxx\ C)}{\Delta A_{abs} (EN\ AW–6xxx)}$$  \hspace{1cm} (3)

$$Q_{Spez} = \frac{\Delta A_{Spez} (EN\ AW–6xxx\ C)}{\Delta A_{Spez} (EN\ AW–6xxx)}$$  \hspace{1cm} (4)

The results of the relative ductility evaluation for all specimen geometries and consolidation areas are displayed in figure 7. It can be seen, that increased ductility for EN AW-6xxx C alloy can be predicted with notched tensile tests even in case of large consolidation areas. The quotient of superior ductility for EN AW-6xxx C alloy increases with decreasing notch radii. Uniaxial tensile tests can reach determine adequate ductility relations for small sizes of consolidation area. If the consolidation area is reduced to single point evaluation all investigated specimen geometries provide similar results with increased ductility for EN AW-6xxx C alloy of about 20-30%.

![Figure 7](image)

**FIGURE 7.** Influence of consolidation area and specimen geometry on the relative ductility of investigated alloys.

4. Conclusion and Outlook

Experimental studies carried out within the scope of this paper investigate various possibilities to characterise ductility of two aluminium 6xxx sheet alloys for the description of their crashworthiness. While material properties gained by regular evaluation of uniaxial tensile test show increased strain values for EN AW-6xxx alloy, evaluation tests with crash-relevant loading conditions such as edge compression test and axial crush test determine increased crashworthiness for EN AW-6xxx C alloy. Even though adequate ductility characterization between the investigated alloys is not possible with the regular evaluation of the tensile test, by focussing evaluation on the necking behaviour potential for determining crashworthiness correctly is given. This is due to the fact, that the loading conditions occurring in the area of localized necking are combined and localized and therefore similar to the critical, crash relevant loads. To optimize this evaluation method reduction of the size of consolidation area shows great potential as irrelevant distributed strain in non-critical areas is excluded. Depending on the evaluation values the increase in ductility for EN AW-6xxx C alloy compared to EN AW-6xxx alloy is about 30 – 35% and therefore in good accordance to the results from ECT.

As the superior ductility characterization by focussing the area of necking in tensile tests is due to the combined, localized loading conditions another approach to reach this critical loading collective is
realised by carrying out notched tensile tests with notch radii $r = 1\ \text{mm}$ respectively $r = 4\ \text{mm}$. Based on the stress concentration within the notched area combined, localized load conditions establish throughout the complete testing phase. Especially with sharp notches it is therefore possible to realise adequate ductility characterization even without the need of reducing the consolidation area. With decreasing notch radius this effect enhances. Based on these results notched tensile tests are potent to determine material crashworthiness with basic mechanical measurement systems. While large differences in ductility assessment can be observed for large consolidation areas between tensile tests and notched tensile tests with different notch radii, the reduction of consolidation area to one single critical point leads to consistent evaluation of the investigated alloys crashworthiness.

Load adapted design of crash-relevant automotive components is essential to access the optimal combination of light-weight design and crash safety. As the methods investigated in this paper are suitable for additional materials such as extrusion or casting alloys, new opportunities for load adapted design of crash-relevant automotive components arise with this approach to ductility characterisation.

5. References

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