

Investigation on crashworthiness characterisation of 6xxx-series aluminium sheet alloys based on local ductility criteria and edge compression tests

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Abstract. In order to satisfy continuously increasing regulations, further improvement of crash performance proves to be one of the major technological challenges of modern automotive engineering. It is crucial to have detailed specifications of material properties available that allow strategic material selection for various applications in future car body design. Within the scope of this work, local ductility of three 6xxx-aluminium sheet alloys is investigated based on evaluation of the localised necking behaviour in post-uniform phases of tensile tests (e.g. true fracture strain). The considered ductility criteria are gained by optical, analytical and fracture surface measurement methods. In addition to that, fracture propagation investigations are carried out to refine the ductility characterisation. The potential of local ductility characterisation methods is validated with results of the Edge-Compression Test (ECT) which allows quantification of material ductility at load conditions that occur in actual crash events.

1. Introduction

In order to satisfy continuously increasing demands in crash-performance in parallel with the increased interest in lightweight construction, 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) investigate material behaviour at planar loading cases and are therefore limited in characterizing crash performance [2] as the loading conditions occurring during various crash scenarios can be three dimensional and often are limited to a relatively local area of the structural body part.

The current method to characterize ductility of sheet and extrusion material under crash relevant loads is the axial crush test of rectangular profiles [3–5]. While for aluminium extrusion optimized sizing of multi-cellular profiles is an approach to increase crashworthiness [6], sheet profiles rely on high material ductility to ensure high energy absorption and fracture resistance. As the material thickness is limited in structure components, impacts during crash scenarios often lead to bending dominated loading conditions. Therefore material testing methods such as the three-point bending test [7] were established to characterise material ductility. Due to the test setup, various possible experimental uncertainties arise and exact bending angle determination is complicated [8].

With the Edge Compression Test (ECT) that was presented in [9] the critical 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 ductility at crash-relevant loads. While this approach focusses on determining the resulting ductility under crash-relevant loading conditions, correlation to the material parameters that lead to these differences in crash performance still has to be carried out.



In the scope of this work ductility criteria based on advanced evaluation of tensile tests are therefore analysed to link the ductility at crash-relevant loads to basic material parameters. The considered ductility criteria are acquired by optical, analytical and fracture surface measurement methods. Validation of the ductility criteria is carried out with ECT. As 6xxx-series aluminium exhibit only slight sensitivity to high strain rates at room temperature [10] all experimental investigations are examined with quasi-static loads.

2. Materials investigated

2.1. Chemical composition

The investigated materials in this study are 6xxx-series aluminium sheet alloys with 2.0 mm nominal thickness. EN AW-6xxx C alloy was developed for increased crashworthiness and is therefore expected to be superior concerning ductility. EN AW-6xxx HS is a high-strength 6xxx-alloy. Table 1 shows the chemical composition of the alloys. Although the composition is relatively similar in most of the elements, reduced silicon and increased magnesium content is detected for the EN AW 6xxx-C.

Table 1. Chemical composition of the test materials.

Material	Si [wt%]	Mg [wt%]	Fe [wt%]	Mn [wt%]	Cu [wt%]	Cr [wt%]	Ti [wt%]	Mg/Si [-]
EN AW-6xxx C	0.71	0.71	0.16	0.13	0.130	0.031	0.014	1.00
EN AW-6xxx	1.09	0.44	0.23	0.14	0.088	0.029	0.026	0.40
EN AW-6xxx HS	0.99	0.64	0.25	0.17	0.165	0.031	0.016	0.65

2.2. Mechanical properties

Uniaxial tensile tests were carried out to characterise the mechanical properties of the mentioned materials. Before testing, the specimens that are initially in T4 condition are age hardened by a heat treatment of 20 minutes at 185°C in an experimental oven. This heat treatment represents a paint bake heat treatment and results in a perception hardening of the material. The resulting mechanical properties obtained after heat treatment are displayed in Table 2.

With regular evaluation of the uniaxial tensile test the increased ductility of EN AW-6xxx C is not evident. This demonstrates the limited potential of crashworthiness prediction based on tensile test.

Table 2. Mechanical properties of the investigated materials gained by tensile tests.

Material	Heat treatment condition	Rolling dir. [°]	Yield Str. $R_{p0.2}$ [MPa]	UTS R_m [MPa]	Uni. elon. A_g [%]	Frac. elon. A_{80} [%]	r-value r [-]
EN AW-6xxx C	Paint	0	187.6	285.7	16.9	20.7	0.7
	Baked	90	172.5	272.6	19.0	24.4	1.3
EN AW-6xxx	Paint	0	167.6	265.1	17.5	23.4	0.6
	Baked	90	169.8	266.3	18.0	23.5	1.1
EN AW-6xxx HS	Paint	0	218.9	313.3	15.2	19.3	0.6
	Baked	90	201.5	300.6	16.6	21.7	1.0

Following investigations in this paper are only carried out in rolling direction as this orientation shows minimal ductility concerning elongations in tensile test. All experimental results are based on a minimum of three valid tests.

3. Advanced ductility characterisation based on tensile test

3.1. Ductility characterisation based on stress-strain behavior

Figure 1 (a) shows the stress-strain-curves of the investigated alloys obtained by uniaxial tensile tests. Strain measurement is realised by a mechanical extensometer with standardised gauge length of 80 mm according to DIN EN ISO 6892-1. The curves show a superior fracture elongation for EN AW-6xxx alloy which indicates the poor ductility characterisation potential based on regular evaluation of tensile tests.

Nevertheless it is possible extend the ductility characterisation based on stress-strain behaviour in tensile tests when using advanced evaluation methods that focus on the post-uniform behavior. In this phase of the tensile test, as a result of necking the loading conditions change and the emerging loads in the critical area are localised and three-dimensional which applies better to crash-relevant loads. The necking behaviour is therefore described in scalar values. Strain based criteria such as the relation of fracture elongation A_{80} and uniform elongation A_g (ΔA_{abs} – eq. 1 and ΔA_{spez} [11] – eq. 2) exist as well as stress based criteria such as the relation of ultimate tensile strength R_m to fracture stress R_b ($\Delta R/R$ [12] – eq. 3) and combinations of the aforementioned (eg. $DV_{postuni}$ [13] – eq. 4).

$$\Delta A_{abs} = A_{80} - A_g \quad (1)$$

$$\Delta A_{spez} = \frac{\Delta A_{abs}}{A_g} \quad (2)$$

$$\Delta R/R = \frac{R_m - R_b}{R_b} \quad (3)$$

$$DV_{postuni} = \sqrt{\left[\ln \left(\frac{R_m}{R_b} \right) \right]^2 + \left[\ln \left(\frac{A_{80} - A_g + 1}{A_g + 1} \right) \right]^2} \quad (4)$$

Results for the investigated advanced evaluation methods are presented Figure 1 (b). While strain based criteria (ΔA_{abs} and ΔA_{spez}) do not improve the ductility prediction, stress based and combined methods show slightly increased ductility for EN AW-6xxx C alloy (+4.1% respectively +2.6% related to EN AW-6xxx) and rate the ductility of EN AW-6xxx HS alloy as poorest (-59% respectively -35% related to EN AW-6xxx).

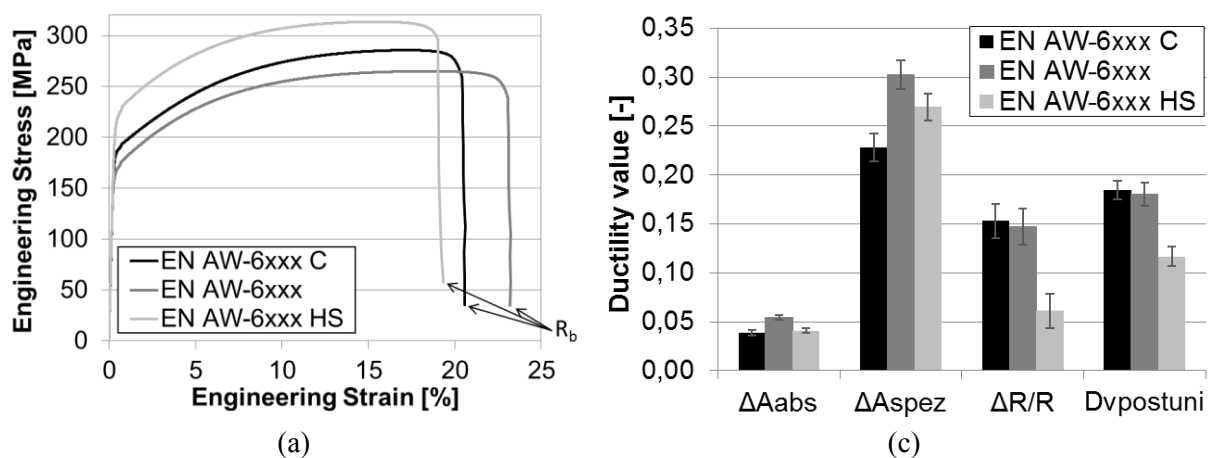


Figure 1. (a) Stress-strain-curve gained by uniaxial tensile tests of investigated materials;
(b) Ductility criteria based on stress/strain behaviour

3.2. Ductility characterisation based on strain measurement with digital image correlation (DIC)

As the area of necking is only a small proportion of the whole specimen, strain evaluation with mechanical extensometer with standardised gauge length of 80 mm cannot be sensitive to local strain behaviour in the post-uniform phase of the tensile test (see results from Figure 1(b)). Therefore another approach to improve ductility characterisation potential is to focus on the post-uniform behaviour of tensile tests by reducing the gauge length for strain evaluation. Tensile tests are therefore evaluated using strain measurement from 3D-DIC based on the GOM-Aramis system. This approach allows variation of the consolidation area after testing. The optical evaluation method with different consolidation areas is presented in Figure 2 (a). As displayed in Figure 2 (b), reduction of consolidation area results in the increase of fracture strain A_f while uniform elongation A_g is relatively constant. Local elongation values gained by single point consolidation area is potent to predict increased ductility of EN AW-6xxx C alloy (+6.0%) as well as inferior ductility of the HS alloy (-16.7%).

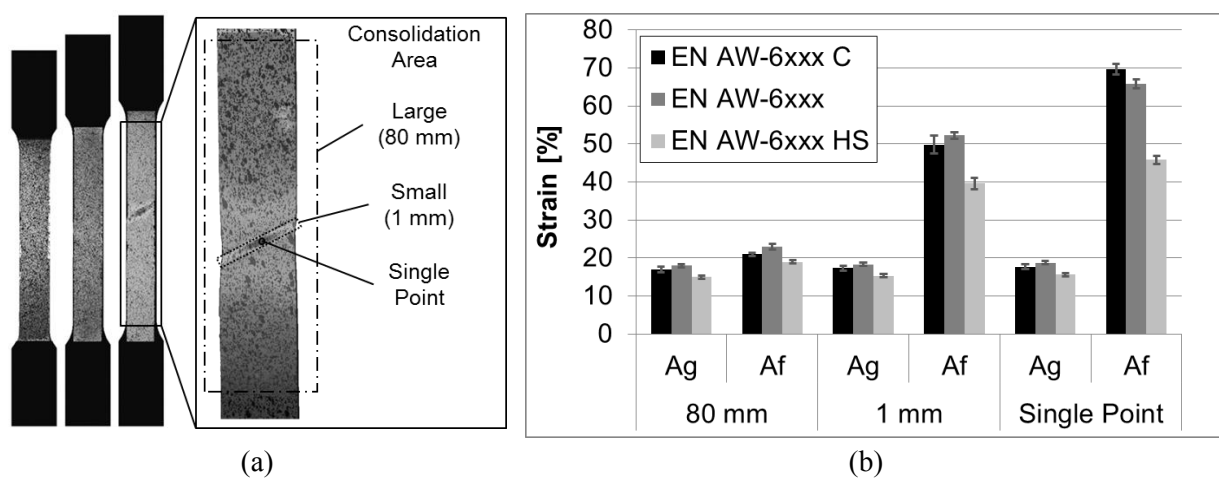


Figure 2. (a) Investigation on tension specimen with different consolidation areas [14];
(b) Influence of consolidation area size on uniform (A_g) and fracture strain (A_f)

3.3. Ductility characterisation based on fracture surface measurement

As already mentioned a large amount of deformation is concentrated in the necked region of a tension test specimen, and therefore the fracture strain depends upon the gauge length. Another possibility to determine local ductility from uniaxial tensile test is by analysing the reduction of area at fracture. The reduction of area Z is insensitive to gauge length and is, according to ISO 6892, defined as the difference between the original cross-sectional area S_0 and the minimum cross-sectional area S_f after fracture:

$$Z = \frac{S_0 - S_f}{S_0} \quad (5)$$

The fracture surface cross-section S_f and mid-thickness t_f can be determined by microscopic measurement (Figure 3 (a)). With the assumption of volume constancy in the necking zone, the Z -value can be converted to A_0 (zero-gauge-length elongation). The corresponding true strain value for zero gauge length is called total fracture strain (TFS) [15].

$$TFS = \ln(1 + A_0) = \ln\left(\frac{1}{1-Z}\right) = \ln\left(\frac{S_0}{S_f}\right) \quad (6)$$

The TFS has been used to characterize local ductility of different materials in various investigations and is found to correspond with crash-performance [16-18]. Results of Z and TFS for the investigated materials are displayed in Figure 3 (b). EN AW-6xxx C alloy shows slightly increased local ductility of 4.2% respectively 6.5% compared to EN AW-6xxx alloy. Inferior ductility of EN AW-6xxx HS compared to EN AW-6xxx can as well be detected with this method (-22.9 % respectively -30.6 %)



Figure 3. (a) Fracture surface measurement (b) Results gained by fracture surface measurement

Results of advanced ductility characterisation methods are summarised in Table 3. It can be seen that the increased ductility of EN AW-6xxx C is evaluated to about 4% - 7% and the decrease in ductility for of EN AW-6xxx HS to 30% - 59% for most of the local ductility characterisation methods. This shows the potential of this approaches, however the quantification of the material ductility evaluation has to be verified by comparing it to material behaviour under crash-relevant loads (see chap. 5). Solely the strain-based evaluation based on stress-strain-curve evaluates the ductility of EN AW-6xxx C alloy as poorest. This can be addressed to the small proportion of post-uniform elongation which leads to a strong weighting of the uniform strain and therefore a more global evaluation.

Table 3. Summary of the results of advanced ductility characterisation methods

Material	A_{spez} [-]	$\Delta R/R$ [-]	$D_{vpostuni}$ [-]	$A_{f,SP}$ [%]	Z [-]	TFS [-]
EN AW-6xxx C	0.228	0.153	0.185	69.72	0.56	0.82
EN AW-6xxx	0.302	0.147	0.180	65.78	0.54	0.77
EN AW-6xxx HS	0.270	0.061	0.117	45.79	0.41	0.53
Increase for EN AW-6xxx C	-24.6 %	+4.1 %	+2.6 %	+6.0 %	+4.2 %	+6.5 %
Decrease for EN AW-6xxx HS	-10.8 %	-58.5 %	-35.3 %	-16.7 %	-22.9 %	-30.6 %

4. Ductility characterisation by fracture propagation investigation

As displayed in Table 3 the advanced local ductility characterisation gained by tensile tests shows a relatively small increase in ductility for EN AW-6xxx C. As the alloy is developed for superior crash performance the increase in ductility should be more significant. To refine crashworthiness characterisation additional approaches have to be carried out. Investigation on crack propagation behaviour seems to be a promising method for determination of local material ductility as the sharp notch in the specimen for the so called Tear-Test (Figure 4 (a)) leads to local, combined loads [19-20].

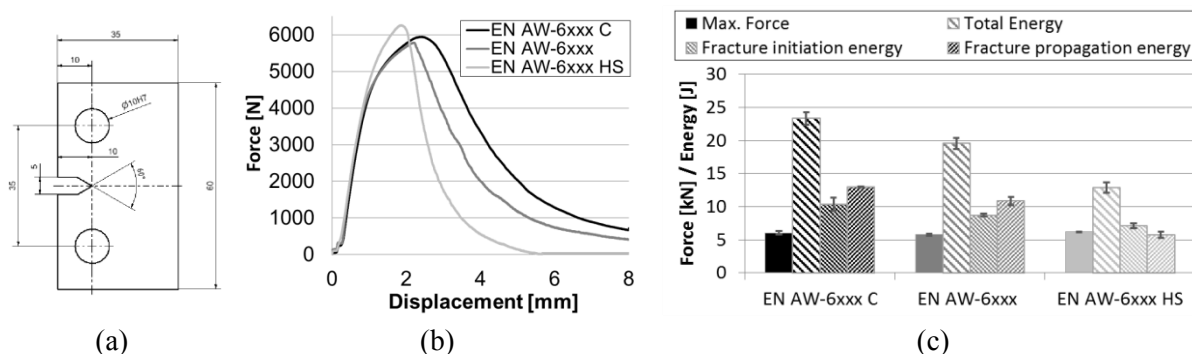


Figure 4. (a) Specimen for Tear-Test [19] (b) Force-Displacement results gained by Tear-Tests (c) Results in force and energy gained by force-displacement behaviour of Tear-Tests

Figure 4 (b) displays the Force-Displacement results gained by Tear-Tests. The peak in force-displacement relation evolves when fracture initiates at the sharp notch of the specimen. The maximum force is superior for EN AW-6xxx HS alloy which can be addressed to its high strength. Fracture initiation displacement as well as the area under the force-displacement curve, which represents the total energy of the test, is increased for EN AW-6xxx C alloy. Splitting up the total energy to fracture initiation energy and fracture propagation allows further refinement of the evaluation. As Table 4 and Figure 4 (c) show, the increase in all energy results is significant for EN AW 6xxx C alloy and therefore the significantly increased ductility can be evaluated.

Table 4. Summary of the results of fracture propagation investigations gained by Tear-Tests

Material	Max. Force [kN]	Total Energy [J]	Frac. initiation Energy [J]	Frac. propagation Energy [J]
EN AW-6xxx C	5.95	23.59	9.60	13.99
EN AW-6xxx	5.79	18.75	8.30	10.46
EN AW-6xxx HS	6.21	12.87	7.13	5.74
EN AW-6xxx C / EN AW-6xxx	+2.81%	+25.79%	+15.73%	+33.75%
EN AW-6xxx HS / EN AW-6xxx	+7.32%	-31.34%	-13.96%	-45.11%

5. Validation with crash performance in Edge Compression Test (ECT)

In [9] Edge Compression Test was established as a method to evaluate and quantify ductility of sheet material in crash-relevant loading conditions. ECT represents a simplification of the axial crush test of a closed hat section as one edge of a rectangular profile is crushed until a defined tool displacement is reached and one single fold is formed. The critical area of the edge compression specimen (the inner side of the evolving fold) is accessible for optical inspection at every step of the procedure. This allows visual evaluation of the material ductility as fracture initiation can be assessed and in situ strain measurement can be applied. Strain measurement has to be treated carefully hereby, as due to the free deformation of the material, strain concentration is influenced by plasticity of the materials (e.g. hardening rates (n-values)). Higher values of equivalent strain ϕ_{eq} before crack therefore do not guarantee increased ductility. The ductility criterion (D_{ECT}) used for evaluation of ECT (eq. 7) is based on the relation of upper tool displacement at fracture d_{frac} to maximal upper tool displacement for the test setup ($d_{max} = 30$ mm). If no fracture occurs D_{ECT} therefore equals 1.

$$D_{ECT} = \frac{d_{frac}}{d_{max}} \quad (7)$$

Table 5 sums up the ductility results from ECT. While EN AW-6xxx C tolerates the emerging loads, EN AW-6xxx and EN AW-6xxx HS specimens showed fracture at the area of the bending line (similar to the results from [9] - Figure 5 (a)). D_{ECT} is increased by 19.5 % for EN AW-6xxx C alloy and decreased by 43.0 % for EN AW-6xxx HS alloy compared to EN AW-6xxx alloy. This shows the significant ductility difference between the investigated alloys under crash-relevant loading conditions.

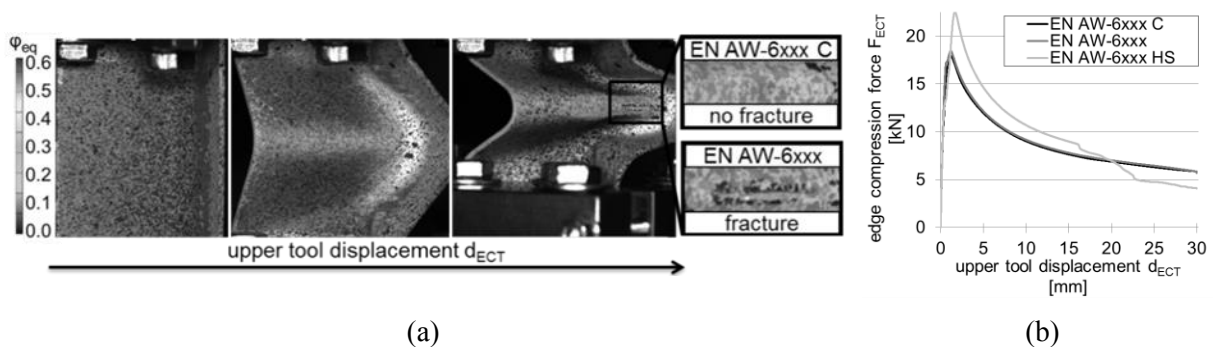


Figure 5. (a) In-situ strain measurement of ECT [9] (b) Force-Displacement result of ECT

Figure 5 (b) displays the force-displacement result of ECT. EN AW-6xxx C and EN AW-6xxx alloy show similar crushing result while the increased strength of EN AW-6xxx HS leads to increased energy absorption in ECT despite showing force drops after the occurrence of fracture at high values of upper tool displacement. This shows that crashworthiness is always influenced by both ductility and strength. Nevertheless this paper focusses on methods for ductility characterisation of materials in crash-relevant loading conditions and it has to be noted that the ECT is rather a material test than a component test and therefore energy assumption is not evaluated.

The ductility results from ECT demonstrate, the improvement of ductility prediction with local ductility evaluation methods based on uniaxial tensile test (see chap. 3) compared to global evaluation methods as the ductility of the investigated alloys is characterised qualitatively correct. Due to the high proportion of uniform forming in tensile tests, the local ductility is hereby still not weighted strong enough and therefore the potential of characterising ductility of investigated materials quantitative is limited. The quantitative results from ECT correlate better with the results from fracture propagation investigations and a combination of local ductility evaluation from uniaxial tensile tests and fracture propagation investigation is therefore promising.

Table 5. Results from Edge Compression Test (ECT)

Material	Inner radius of Specimen [mm]	Max. upper tool displ. d_{\max} [mm]	Upper tool displ. until fracture d_{frac} [mm]	ECT Ductility Value D_{ECT} [-]	D_{ECT} related to EN AW-6xxx
EN AW-6xxx	8.0	30.0	25.1	0.84	-
EN AW-6xxx C	8.0	30.0	30.0	1.00	+19.5%
EN AW-6xxx HS	8.0	30.0	12.9	0.47	-43.0%

6. Conclusion and Outlook

Experimental studies carried out within the scope of this paper investigate potential of local ductility criteria for evaluation of uniaxial tensile tests to determine ductility of aluminium 6xxx sheet materials in crash-relevant loading conditions.

The focus of the investigated methods is on the post-uniform phase of tensile tests as in the area of localized necking loading conditions occur that are local and non-uniform and therefore similar to crash-relevant loads. The considered ductility criteria are acquired by optical, analytical and fracture surface measurement methods. The potential of local ductility characterisation methods is validated with results of the Edge-Compression Test (ECT). While ductility criteria based on local evaluation of tensile tests are not sensitive enough to predict the increased ductility of EN AW-6xxx C alloy accurately, refinement of the existing criteria with results from fracture propagation investigation leads to adequate ductility characterisation. Based on the ECT and the possibility to quantify material ductility at loading conditions that occur in actual crash events, ductility criteria can be evaluated. Different approaches can be combined to allow for a reliable ductility prediction based on material parameters rather than component testing. As the methods investigated in this paper are suitable for additional materials such as steel sheets, aluminium extrusion or casting alloys, new opportunities for load-adapted design of crash-relevant automotive components arise with this approach to ductility characterisation.

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