Chapter 9

Fracture behavior of low density replicated aluminium alloy foams

The role of several factors that influence the mechanical response has been assessed in the previous chapters except for the role of the topology. In this chapter, the fracture behavior of an open-cell foam with a different topology than Duocel open-cell foam is described. The microstructure and the sample properties, which include the relative density, shape and size, are kept as similar as possible, so that the results on this foam can be compared to the results on Duocel foam. In contrast to Duocel, the mechanical properties are isotropic and the ratio between the squareroot of the cross-section and the length of the sample is exactly the same as for the Duocel foam samples. The relative density range is also within the range of the Duocel foam samples.

9.1 Introduction

It was shown in Chapter 6 that, in ERG Duocel AA6101 aluminium alloy open-cell foams, both the rate of damage accumulation and the average sample peak strain display an interesting dependence on relative density: as the relative density falls below roughly 5.5%, the less dense the foam, the higher becomes its tensile ductility. It was also shown that this increased ductility of low-density foams is accompanied by a decrease in the rate of damage accumulation and an increase in the relative contribution of strut bending during deformation, the latter being due to the fact that, by changing the density at constant cell size, the thickness and the shape of the struts are changed.

In the work reported in this chapter, we explore whether the same phenomenon can also be observed in another open-cell metal foam, similar to the material investigated in Chapter 6, but produced by Replication processing [1] instead of
investment casting. The resulting material has a mesostructure different from that of the ERG material, as its structure and struts are less regular and more material is located at the nodes (see Figure 9.1). The high ratio of specimen size to cell size of the replication-processed samples made it feasible to employ the digital image correlation (DIC) technique for mapping the local strain at the surface of the sample as a function of the overall strain. During the uniaxial tensile tests the electrical resistance was also measured in order to gain insight on damage evolution inside the specimen. Additionally, the strain maps of the surface were used to examine the location of damage evolution during sample deformation.

9.2 Material and experimental procedure

Open-cell aluminium alloy foam, with a cell size of about 400 μm, was produced following the replication process (see Chapter 2 and Ref. [1]) at the Ecole Polytechnique Fédérale de Lausanne (EPFL) by R. Goodall. In total seven tensile samples were produced in a single infiltration using 400 μm mean diameter salt particles and an infiltration pressure of 4 bar. The alloy used for the production of the present samples was a 6xxx-series alloy similar to AA6101, of composition specified by the supplier (see Table 9.1). The samples were machined before dissolution of the salt. The shape of the samples was cylindrical and the diameter of the reduced section was 8 mm and the length was 17 mm; the total length of the sample was 24 mm. A tensile stage made by Kamrath&Weiss was employed for the
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Table 9.1 Al alloy composition (wt%) of the precursor and the foam. The composition of the precursor was specified by the supplier.

<table>
<thead>
<tr>
<th>element</th>
<th>Mg</th>
<th>Si</th>
<th>Fe</th>
<th>Mn</th>
<th>Ti</th>
<th>Zn</th>
<th>Cu</th>
<th>Cr</th>
<th>Pb</th>
<th>Na</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precursor</td>
<td>0.47</td>
<td>0.40</td>
<td>0.20</td>
<td>0.019</td>
<td>0.014</td>
<td>0.010</td>
<td>0.006</td>
<td>0.004</td>
<td>0.002</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

tensile tests using a rate of displacement of 3 \( \mu \text{m/s} \) and a 100N load cell. The foam samples were glued to aluminium T-bars using an epoxy glue (Araldite 2011) produced by Vantico. The overall strain was calculated by the displacement (measured by DIC) of markers at the beginning and end of the reduced section. The local strain was measured by digital image correlation (DIC) (Aramis software, produced by GOM mbH). The average of the local strain equals the overall strain measured by the displacement of the markers.

During the tensile tests, the resistance was monitored using a 4-point measurement set-up. A 3A current ran through the sample, produced by a Keithley 2601 system source meter. The polarity of the current was alternating with a frequency of 1 Hz to eliminate thermocouple effects and the wires were connected at both ends of the sample. The resistance was measured with a Keithley 2182 nanovoltmeter using an electrode soldered to the foam at the beginning and an electrode at the end of the reduced section. The markers for the overall strain were located near the electrodes. The samples were isolated from the T-bars and the tensile stage by the glue.

9.3 Results and discussion

The topology of the foams produced here is shown in Fig. 9.1. It differs significantly from that of the ERG Duocel foam investigated in Chapter 5 and 6: the scale is finer and the mesostructure is more irregular. The struts have a plate-like appearance, presumably due to the shape of the open pore space left between flat facets of the salt particles in the preform. AlSiFe-precipitates, also found in 6101 ERG Duocel foams (Chapter 5), are visible along the free surface of the metal. An EDS area scan indicates the presence of the main alloying elements (Table 9.1). The present foams are of much lower relative density than replicated aluminium foams produced in earlier studies of this material [2,3,4,5,6]; the most salient difference with higher-density replicated aluminium foams is that in the present, low density, foams the struts are very thin in their mid-section (see Fig. 9.1).

Figure 9.2 plots the 0.2% offset yield stress and the stiffness of the foam samples as a function of the relative density, \( \rho_r \). The 0.2% offset yield stress scales
with the relative density to the power 3.7, whereas the stiffness scales with the relative density to the power 4.3. A power of 3.7 for the yield stress is high compared to the power 1.5, predicted by the Gibson & Ashby relationship [7]. Comparatively, Eq. 8 of Ref. [8] predicts that the yield stress should vary as $\rho_r^{3.1}$ if the Young’s modulus scales as $\rho_r^{4.3}$ and the solid strain hardening exponent $n_s = 0.256$ as measured for annealed 6101 alloy (Chapter 6). It should also be noted that the total number of samples as well as the density range measured here is limited. For pure Al samples in a higher density range the exponent for the 0.2% yield stress is approximately 2.7 [9].

Figure 9.3 shows the peak strain as a function of the density. The observation reported in (Chapter 6) for Duocel foams is confirmed here, namely that the peak strain increases sharply when the density decreases below 5.5%. Note that the 6.5% relative density sample gives two data points, because it exhibits two peaks in the overall stress-strain curve (see Fig. 9.5).

The DIC software was used to measure the local strain at the surface of the specimen. Figure 9.4 shows the local strain along the tensile direction as a function of position along the gage length of a sample of 5.3% relative density. The strain is localized in bands, which are already present right from the start of the tensile test. In each band the strain develops proportionally with increasing overall strain, as shown in Fig. 9.4. For overall strains up to 1.5% the same observation holds for all the samples, but there are differences in the detailed morphology of the bands. Similar results have also been reported for open-cell nickel foam [10].

Above 1.5% overall strain, the local strains have increased so much that fracture
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Figure 9.3 Peak strain as a function of the relative density. The 6.5% sample has two peak strains, because the overall stress-strain curve has two peaks of equal stress (see Fig. 9.5).

Figure 9.4 Local strain along the gage length of the 5.3% density sample for three different overall strains. Bands of high local strain can be observed and the morphology of the bands differs among the samples.

usually occurs in the band with the highest strain. However, for the 6.5% relative density sample complete fracture did not occur after the first peak in the band with originally the highest strain, but in another band after the second peak in the stress-overall strain curve (see Fig. 9.5). The incremental strain maps in Fig. 9.5b show that just before the first peak most of the deformation occurs in a single band, until
Figure 9.5 (a) Stress-overall strain curve of the 6.5% relative density sample. The sample has two peaks of equal stress (indicated by the arrows). Map 1 and 2 and the vertical lines correspond to Fig. 9.5b. (b) Incremental strain maps of a specific area of the 6.5% relative density sample. In that specific area the incremental local strain was much higher than in the rest of the sample. Map 1 is calculated by comparing the image at 1.40% overall strain to the image at 1.34% overall strain. Map 2 is calculated by comparing the image at 1.72% overall strain to the image at 1.62% overall strain. The tensile direction is in the vertical direction and the width of the maps is the same as in Fig. 9.6.

it stops after the first peak and then proceeds in another band. This behavior closely resembles the behavior under compression, where initially-formed bands harden, spreading deformation to new bands in neighboring regions [11]. Besides the 6.5% relative density sample a single band, i.e. that with originally the highest local strain, is involved in the fracture phenomenon for densities above 5.5%.
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For samples below 5.5% relative density, however, the number of bands, which are involved in the fracture process, increases with decreasing density, an example of which is depicted in Fig. 9.6. For this 4.5% relative density sample, the following behavior was observed from the incremental strain maps. First the deformation was largest in one band; then it stopped and continued in another band. With increasing overall strain the deformation also stopped in the second band and then continued again in a third band. Finally, a fourth band formed, after which the deformation started again in the original band. The sequence of the deformation bands then remained fixed and repeated itself for 3 cycles on a longer timescale; at a shorter timescale the local incremental strain oscillated somewhat between bands. The sample failed completely in the first, most highly strained band. Unlike the 6.5% relative density sample, the overall stress-strain curve does not show softening before the peak stress. These observations imply the presence of a mechanism by which strain localization causes an increase in hardening of the material, which in turn stabilizes it against tensile instability. This hardening mechanism increases in intensity as the relative density decreases, which in turn, explains the increasing tensile ductility that is found as the relative density of the foam decreases below 5.5 % (see Fig. 9.3).

Figure 9.6 Incremental strain maps of the 4.5% relative density sample and an image of the sample. The white rectangle in the image of the sample indicates the original area of the maps and the maps are calculated by comparing the images at the indicated overall strains to each other.
The superposition of multiple individual power-law relations with the same exponent yields a power-law relation with the same exponent. The overall stress-strain curve of the various samples exhibits a power-law hardening behavior (see Fig. 9.5). From DIC it can be concluded that the stress-strain curves of different bands in a sample have about the same shape. Assuming that the strain localization documented in Figs. 9.4 to 9.6 is due to density variations within the specimen, then the density of the band with the highest strain should be lower than the measured mean density of the sample (and conversely, the density of the band with the lowest strain should lie above the mean density of the sample). On this basis, the stress at which a strain of 0.5% is reached in a band can serve as a measure for the density in that band since the flow stress depends strongly on the relative density of these materials. Estimating in this manner (details are given in Appendix A), the densities of the bands from the stress at 0.5% strain, it is found that a scaling law with a power of 3.8 is needed to have all the measured densities of the samples between the calculated density limits (see Fig. 9.7). Hence, this estimation of the cause for variation in strain along the foam samples is consistent since it yields roughly the same power as the scaling of the yield stress with sample density found from the average foam densities (Fig. 9.2), namely 3.7. It is thus reasonable to conclude that the observed strain localization is due to initial density variations in the samples. As seen in Fig. 9.7, the estimated spread in relative density is on the order of 10%; this spread in density within the samples is similar to the reported values in Ref. [12] for replicated foam of higher densities.

During the tensile test, the electrical resistance was measured and from the initial slope of the relative resistance as a function of strain the value of $q$ can be obtained (see Eq. 7.1). This value of $q$ reflects the contribution of uniaxial stretching compared to bending at the mesoscopic scale in the foam in the early stages of foam deformation: more deformation by bending will lead to a decrease in the value of $q$. When bending is dominant, the struts will orient towards the loading direction with further straining, which will increase the local flow stress by changing the local geometry of the structure; we define this hardening mechanism of porous materials as “geometric hardening”. Fig. 9.8 shows the $q$-value as a function of the density: as seen, it decreases below unity for relative densities below 5.5%. This indicates that there is more bending deformation in the low density samples. This suggests a higher degree of geometric hardening as the foam relative density decreases, which in turn can explain why the material is observed to become increasingly stable against strain localization as its relative density decreases.

A comparison of the two sets of data, for the present metal foams and the ERG
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Figure 9.7 Density of the band with the highest strain (triangle down) and with the lowest strain (triangle up) as a function of the measured mean density of that sample (solid line). The densities of the bands are calculated by using the stress at 0.5% strain and the scaling law (see Appendix A), a power of 3.8 is needed to have all the measured mean densities of the samples between the calculated densities of the bands.

Duocel material characterized in Chapter 6 (compare Figs 6.4 and 6.10 of Chapter 6 with Figs. 9.3 and 9.8 of the present work, respectively), suggests that not only the trends, but the absolute values are quite similar: indeed, the present data for both the peak strain and the measured $q$-values are similar across the two studies. This finding is a priori surprising, because the structure and shape of the struts, and also the intrinsic load-bearing efficiency (see Figs. 6 and 7 of Ref. [4]) of the two open-pore foam types, are very different.

Fig. 9.9 shows the relative resistance, normalized by Eq. 7.1 using $q$ values derived from the initial slope of curves giving measured relative resistance versus strain (Fig. 9.8). Assuming that the initial foam deformation sees little internal damage, and that these values of $q$ remain characteristic of the mode of foam deformation, the excess change in resistance must be due to damage accumulation. These relative resistance curves are thus correlated to the total damage experienced in the sample between the sensing electrodes. The relative resistance curves are plotted as a function of the strain until the peak strain reached by the relevant sample.

The focus of Fig. 9.9a lies on the high density samples with a peak strain of about 1.5%. The lower two out of the four curves correspond to the 6.0% and 7.9% relative density samples. For these samples, fracture occurred in a band with the
Figure 9.8 $q$-value (see Eq. 7.1) as a function of the relative density. Resistance measurement data of the 4.6% density sample was lost and therefore not depicted here.

highest strain, which was located outside the electrical resistance measuring area. Therefore, the change in resistance is a measure for the damage outside the final fracture area: the data indicate that damage does not only occur in the fracture area, but develops throughout the sample. The upper two curves are for samples where the highest-strain fracture band was situated between the electrodes; these data thus account for damage both inside and outside the fracture area. The final relative resistance value of the 6.5% relative density sample at the first peak (indicated by the triangle, see Fig. 9.5a) is higher than the final value of the 6.0% and 7.9% relative density sample: the difference being 0.0128. It is expected that the difference is the resistance increase that originates mainly from the damage that occurs in the initial fracture band (Map 1, Fig. 9.5b). The relative resistance value of the 6.5% relative density sample at the first peak of its stress-strain curve is also higher than that of the 6.7% relative density sample at the same strain. This suggests that the damage in the initial band of the 6.5% sample equals or exceeds that in the fracture band of the 6.7% relative density sample at that overall strain. That fracture did not occur in the initial deformation band of the 6.5% sample suggests that the tolerance to damage in that band is higher than that in the 6.7% relative density sample. After the first, peak the overall stress-strain curve decreases, and then increases again until a second peak appears that has the same peak stress, Fig. 9.5a. This can only occur if the initial band experiences, past a certain strain, a degree of local hardening higher than elsewhere along the sample. Fracture of struts contributes to the decrease in stress after the first peak and it is
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Figure 9.9 (a) Relative resistance due to damage as a function of the overall strain for the samples with a relative density above 5.5%. The measured relative resistance was normalized to the value predicted by Eq. 7.1 to yield the relative resistance due to damage. The fracture area of the 6.0% and 7.9% samples was located outside the electrical resistance measuring range. The triangle indicates the relative resistance at the initial peak of the 6.5% sample. (b) Relative resistance due to damage as a function of the overall strain for the 6.7%, 5.3% and 4.5% samples. The final value increases with decreasing relative density. Resistance measurement data of the 4.6% density sample was lost and therefore not depicted here.

expected that this hardening comes from the orientation of struts to the tensile direction, i.e. geometric hardening. It is likely that the additional increase in relative resistance at the second peak as compared to the first peak (i.e. 0.0152) predominantly originates from the damage in the initial and second band, because the incremental strain in the rest of the sample is small. This increase is comparable to the 0.0128 increase between the final relative resistance value at the first peak for this sample and that of the 6.0% and 7.9% relative density samples at the same strain.

Fig. 9.9b shows corresponding data for densities below 5.5%: as seen, the rate of damage accumulation is lower than for higher densities at strains below 1.5% (see also Fig. 9.9a). The lower rate of damage accumulation for the low density samples (<5.5%) is likely to be an effect of the increase in strut bending that is indicated by the decreasing $q$-value, Fig. 9.8 (Chapter 6). Strut bending is accompanied by pronounced plastic deformation, but does not necessarily induce damage. Previous studies have indeed shown that a tensile component is needed for a strut to fail [13].
A clear dependence of the final relative resistance value on the density can also be observed in Fig. 9.9b. From the incremental strain maps of these samples (of less than 5.5% relative density), it is seen that the number of bands involved in the fracture process increases with decreasing density (see also Fig. 9.6). In the 4.5% relative density sample, four bands were involved and the deformation increased and stopped in each band 3 times. The final relative resistance value of this sample is 1.174, which corresponds to an increase of about 12 times the increase caused by one band (=0.0128 for the 6.7% relative density sample). From Fig. 9.9a and 9.9b it can thus be concluded that the final relative resistance value scales with the number of bands involved in the fracture process.

9.4 Conclusion

Right from the start of the tensile test the strain is not uniformly distributed over the length of the replicated aluminium alloy foams sample, but concentrates in bands due to density variations along the gage length of the samples. For average sample densities above 5.5%, fracture usually occurs in the band with the highest strain. For average sample densities below 5.5%, a decrease in the contribution of tensile strut deformation lowers the rate of damage accumulation and increases the tolerance to damage. This ensuing increase in damage tolerance, coupled with an increase in rate of work hardening likely to be caused by the gradual alignment of struts along the tensile direction (which we call geometric hardening), allows a highly deformed band to harden shifting the deformation to another band that leads to more strain accumulation in the rest of the sample. As a result, for relative densities below 5.5%, the peak strain increases with decreasing density, because the number of bands involved in the fracture process increases with decreasing relative density. The present data confirm the findings of Chapter 6 with respect to another, mesoscopically quite different, foam of aluminium alloy 6101, while pointing to a different mechanism that allows these low density replicated aluminium alloy samples to reach such a high peak strain.

Appendix A

This section explains the procedure that was used to arrive at Fig. 9.7. Assume a density variation (around a mean value) along the length of a foam sample. The area and the force in tension are uniform along the length of the sample and therefore the stress is uniform along the length of the sample at each moment during the tensile test. Since in the present work the local strain distribution was
measured along the sample, local stress-strain curves can be constructed for different bands along the sample. Each local stress-strain curve depends on the local density, but it has the same shape, because the strain hardening exponent is independent of the density at low strain. Therefore the local strain evolution as a function of global stress is a measure for the local density along the sample. Two identical local stress-strain curves thus correspond to the same local density; however, what this density is remains unknown without further calibration.

When 5 samples with increasing mean density and the same density variation are measured and a value for the lowest density band (which is the highest strained band of the lowest mean density sample) is set, then the densities of all the other bands can be calculated by using the scaling law and the stress ratios at a certain fixed value of local strain (taken here at 0.5% strain):

\[
\frac{\sigma_1}{\sigma_2} = \left(\frac{\rho_1}{\rho_2}\right)^P
\]

(A9.1)

Clearly the mean density value of the samples imposes a boundary condition on the calculated densities of the lowest and highest strained band of the samples, i.e. these should respectively be above and below the mean value. Thus, the calculated densities depend only on (i) the value set for the lowest density band and (ii) the power of the scaling law, P. In Fig. 9.7 a value for the lowest density band of 4.13% and a P-value of 3.8 (which is near the exponent found for the 0.2% offset strain foam yield stress, namely 3.7) are needed to generate the best fit.

References