Tensile failure of thin aluminium sheet observed by in-situ EBSD

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Abstract. Tensile tests on two similar 75-µm-thick aluminium sheet materials were carried out inside a scanning electron microscope equipped with an electron backscatter detector. The materials were subjected to simulated brazing prior to the test because this type of material is used for fins in automotive heat exchangers. Grain sizes were large relative to sheet thickness and ND-rotated cube and P texture components dominated the recrystallization textures; their volume fractions differed strongly in the two different materials, though. Strains over the microscope image fields were determined from positions of constituent particles or from grain sizes; the two methods gave consistent results. Grains with high Schmid factors accumulated significantly more deformation than grains with low Schmid factors. Cracks nucleated in high-Schmid factor grains, or in groups of such grains, at the specimen edges. When only low-Schmid factor grains were present at the specimen edges, the crack nucleated inside the specimen. The subsequent crack growth was intragranular and occurred at approximately 90° relative to the load direction.

1. Introduction

The onset of plastic deformation in single crystals of aluminium is influenced by the orientation of the crystal lattice relative to the load direction according to Schmid’s law [1]. In polycrystalline materials, grain-to-grain interactions complicate the situation, especially for fine-grained materials where the grain size is significantly smaller than the smallest sample dimension.

Aluminium materials for aluminium heat exchangers have large grains after brazing [2]. This is especially significant for the thin fin materials where grain lengths in the rolling direction often reach a few hundred micrometers while thicknesses are typically between 50 and 100 µm. Sometimes, grains also extend over the complete thickness. Therefore, grain interactions are expected to be smaller in these materials as compared to most other engineering materials.

Fin materials are responsible for the major part of the heat exchange between air and heat exchanger. They are typically formed into wavy shapes and placed between tubes or plates of the respective heat exchanger. Due to this geometry, the mechanical loading usually occurs in the rolling direction of the material.

On a polished tensile test specimen, the evolution of surface morphology and changes in the crystallographic orientation of the surface layer can be investigated in a scanning electron microscope (SEM) equipped with a detector for analysis of electron backscatter diffraction (EBSD). In our contribution, we present details of tensile plastic deformation and fracture of two aluminium fin materials that differ mainly with respect to their texture. Tensile tests with small specimens were performed both inside and outside of the SEM.

2. Experimental procedure

75-µm-thick aluminium materials produced by Gränges AB, Sweden, were selected for this study. The most important production steps of these materials are direct-chill casting, hot rolling and cold rolling. However, we did not sample material from standard commercial materials. Instead, we chose materials from development stages which exhibited texture variations that made them interesting for our present study. Compositions were determined from melt charges by optical emission spectroscopy and are given in Table 1.

Before any testing, the material was subjected to a simulated brazing procedure that included heating to 600 °C, soaking for 3 min at 600 °C and subsequent fast cooling in forced air.
During brazing of aluminium heat exchangers, the material is heated to 600 °C and kept there for a few minutes. Since the materials of this investigation were heat exchanger materials, we intended them to be in the same state as in the product.

Table 1: Composition determined by optical emission spectroscopy.

| Material | Si (wt.%) | Fe (wt.%) | Mn (wt.%) | Zn (wt.%) | Zr (wt.%) | Ti (wt.%) |
|----------|-----------|-----------|-----------|-----------|-----------|-----------|
| A        | 0.77      | 0.23      | 1.61      | 1.46      | 0.12      | 0.04      |
| B        | 0.84      | 0.26      | 1.62      | 0.03      | 0.12      | 0.03      |

Regular tensile tests followed the ISO6892-1:2009 standard. Tensile tests with small specimens were carried out on a Gatan-Deben microtest stage that could be inserted into a Hitachi SU-70 field emission gun SEM. The parallel section of the small specimen covers an area of 5 mm x 5 mm. More details of this setup and of the test procedure were provided in reference [3].

3. Results and discussion

Results from regular tensile tests are provided in Table 2. Material B has slightly higher strength values but a smaller elongation to fracture.

Table 2: Tensile test results in rolling direction on material after simulated brazing, determined from tensile tests according to ISO6892-1:2009.

| Material | Thickness (µm) | Yield strength (MPa) | Tensile strength (MPa) | Elongation to fracture (%) |
|----------|----------------|----------------------|------------------------|---------------------------|
| A        | 75 µm          | 54                   | 135                    | 8.5                       |
| B        | 75 µm          | 60                   | 138                    | 5.7                       |

Material B has larger grains than Material A as shown in Table 3. Most grains of the investigated specimen of Material B have a <111> crystal direction parallel to the rolling direction (RD). For Material A, the fraction of grains with <111>||RD is similar to the fraction of grains with <120>||RD. It is interesting to investigate materials that contain these two types of grain orientations because the Schmid factor for loading parallel to RD is only 0.27 for <111>||RD but has a high value of 0.49 for <120>||RD. Most grains with <111>||RD are represented by the P-texture component while the cube texture component with a rotation around the normal direction (ND) of the rolled sheet stands for most grains with <120>||RD.

Table 3: Grains sizes and volume fractions of texture components, allowing a maximum of 15° deviation from the ideal orientation.

| Material | Grain size | <111> || RD | {111}{110} <110> P-texture | <120> || RD | {001}{120} ND-rot. cube |
|----------|------------|----------|-----------------------------|----------|------------------------|
| A, specimen 1 | 54 µm (256 grains) | 39%      | 33%                         | 36%      | 24%                    |
| A, specimen 2 | 47 µm (205 grains) | 37%      | 31%                         | 36%      | 19%                    |
| B        | 113 µm (661 grains) | 82%      | 82%                         | 4%       | 4%                     |

We tested two different simple methods to determine strain over the SEM field of view. The first one is based on the change in distances between particles, as described in detail in reference [3]. The second method calculates strains from the change in sizes of bounding boxes that surround individual grains. Both methods require manual identification of the features (particles or grains) that should be included into the strain calculation. The particle method gave consistent results: In the case where the strain \( \varepsilon \) could be determined directly from two images or as the sum of several strain steps \( \varepsilon_1, \varepsilon_2, \varepsilon_3 \), we obtained \( \varepsilon = \varepsilon_1 + \varepsilon_2 + \varepsilon_3 \) within better than 0.1% strain. Resolution and accuracy of the grain method depends strongly on the step size of the EBSD measurement. In the present investigation, we only reached a resolution of approximately 1% strain. However, accuracy is improved by averaging over
many grains; when we averaged over 60 grains we obtained the same result as from the particle method, within 0.1% strain.

The strains measured with the particle method in neighboring fields of view in the central region of specimen 1 of Material A as well as corresponding orientation maps are given in Figure 1. Fields of view numbered 2 and 3 contained a larger region of connected “blue grains” and thus exhibited smaller strains than fields of view numbered 1 and 4. “Blue grains” with low Schmid factors accumulate less deformation than “yellow grains”.

![Figure 1: Orientation map in inverse pole figure coloring of the central region of specimen 1 of Material A.](image)

The nucleation and growth of a crack in specimen 2 of Material A is depicted in Figure 2. The crack nucleated in a group of “yellow grains” near the upper specimen edge and then propagated at right angle to the load direction. Prior to rupture, the main crack made a sharp turn in order to meet a secondary crack that started at the lower edge, presumably in another group of “yellow grains”. At 9% strain, the indication of a localized through-thickness necking at an angle of 50°-60° to the load direction is visible and indicated by the white arrows. Such a local neck may be expected for isotropic, thin, homogeneous sheet specimen [4]. However, in the presented case as well as for all other specimens tested in the project, the fracture was dominated by crack initiation and growth. We did not observe indications that growth was influenced by crystallography.

From Material B, we prepared a specimen that contained only “blue grains” with the exception of two large central “yellow grains”, as shown in Figure 3, and two small “yellow grains”. Deformation was strongly localized by the presence of the two large “yellow grains” and the crack started at a grain boundary triple junction at the upper grain boundary of the upper “yellow grain”. Except for a very short distance above the crack nucleation point, crack growth was exclusively intragranular. Nevertheless, crack growth in this specimen contained a crystallographic aspect because the crack changed direction each time a grain boundary of a misorientation angle above 10° was crossed.
6. Conclusions
We prepared thin aluminium sheet materials that mainly consisted of large grains with \(<111>||RD\) and \(<120>||RD\). The deformation and fracture characteristics of tensile tests parallel to RD were determined by the spatial distribution of these two types of grains: Grains with \(<120>||RD\) accumulated more strain than grains with \(<111>||RD\), fracture nucleated in groups of \(<120>||RD\) grains, and cracks grew perpendicular to the load direction.

References
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