Study of elasto-plastic deformation in a cast AlCu7 alloy

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Abstract: The need for efficient and clean solutions, due to the increasing current environmental regulations puts extra pressure on new combustion engine development, to compete in a market with alternative driving concepts. Downsizing and weight reduction can reduce the engine emission and efficiency, but require light alloys with superior thermo-mechanical properties for high temperature exposure to maintain the same engine performance. Cast Al-Cu could be alternative to standard Al-Si alloys for new engine generations due to their higher temperature strength, creep-resistance and long term stability of engine components. In Al-Si and Al-Cu cast alloys with heterogeneous microstructures a composite-like deformation behavior is responsible for superior high temperature properties. Stiff Si or Al₂Cu particles, respectively reinforce a ductile α-Al matrix to a composite with improved thermo-mechanical strength. However, different Young’s moduli and coefficients of thermal expansion are responsible for micro stress gradients and unpredictable micro crack formation under operation. These micro-mechanical deformation mechanisms in Al-Si and Al-Cu systems, responsible for crack initiation and growth, have been scarcely investigated so far.

This manuscript describes an example of elasto-plastic deformation mechanisms in an AlCu7 alloy. Tensile testing shows anomalous macroscopic deformation behavior indicating unknown internal micro-mechanical processes. External loading until yield strength and beyond are applied under laboratory conditions and during in-situ neutron diffraction. The results of macroscopic deformation and micro strain evolution are compared and correlated with the heterogeneous micro structure. High resolution synchrotron computed tomography reveals conclusions on the micro-mechanic deformation mechanisms and their effects on the macroscopic damage initiation and material’s service performance.
1. Introduction
Modern combustion engines put high demands on materials thermo-mechanical properties and long term stability under service conditions [1]. Reduction of fuel consumption and emission going with higher power densities realized in downsized combustion engines is required to fulfill environmental regulations and to stay competitive with alternative drive concepts. Therefore Al-Cu cast alloys could be an alternative to the standard Al-Si alloys for cylinder head production due to their superior properties at elevated temperatures [2]. Al-Si and Al-Cu cast alloys consist of a heterogeneous microstructure which is responsible for their sophisticated thermo-mechanical properties [3]. This cast alloys show a composite-like deformation behavior with stiff and brittle reinforcing primary phase (Si particles in Al-Si alloys and Al₂Cu particles in Al-Cu alloys) embedded in a ductile α-Al matrix [4, 5]. High temperature strength and creep resistance are resulting from stress distribution in between the phases and dislocation accumulations at their interfaces [6]. Problems can rise with the formation of high micro stress gradients in between the phases under cycling loads, which act as potential sources for fatigue damage [7]. These micro-mechanical deformation mechanisms leading to micro cracks, crack propagation and failure of engine parts are strongly dependent on the type of the reinforcing phases, their interfaces with the matrix and their 3D architecture (i.e. interconnectivity) [8]. The investigation of such material properties require highly sophisticated non-destructive methods to study the materials fundamental micro-mechanical behavior under simulated service conditions.

A commercially cast AlCu7 alloy was studied with focus on micro structure, mechanical properties, micro stress evolution and crack initiation. AlCu7 contains primary Cu-Mn-Fe aluminides and eutectic regions of α-Al₂Cu / α-Al in the as cast condition (T1) by non-equilibrium cooling: ~ 6,5 vol.% of α-Al₂Cu aluminides within the eutectic regions [9]. The mismatch in the elastic moduli (E₃₉Al ~ 70 GPa, E₃₉Al₂Cu ~ 100 GPa) and the thermal expansion (CTE₃₉Al ~ 25 ppm/K, CTE₃₉Al₂Cu ~ 17 ppm/K) leads to a composite structure which is also partially responsible for the superior thermo-mechanical properties of AlCu7 [10].

This work describes micro-mechanical deformation behavior in an AlCu7 alloy by application of complementary non-destructive testing methods using photons and neutrons as probe particles. Micro strains where measured phase-sensitively by neutron diffraction (ND), in-situ during tensile testing. Crack initiation and damage propagation was visualized in 3D by high resolution synchrotron computed tomography (SCT). Characterization of the microstructure was performed by light optical micrographs (LOM).

2. Experiment
2.1. Material
A cylinder head was cast with an AlCu7 alloy (NemAlloy HT200) at Nemak Linz GmbH by rotatory gravity die casting (Rotacast®) [11]. Test specimens were prepared from regions close to the heat exposed zones at the fire faced areas on top [1]. The average alloy composition is listed in Tab. 1.

| Type  | Cu [wt.%] | Mn [wt.%] | Ti [wt.%] | Zr [wt.%] | Al [%] |
|-------|-----------|-----------|-----------|-----------|--------|
| AlCu7 | 6.5       | 0.45      | 0.11      | 0.22      | Bal.   |

Table 1.: Composition of investigated alloy.

Tensile test specimens were manufactured accordingly to DIN 50125: 2009-07 in cylindrical shape parallel to the surface. Light optical microscopy (LOM) shows AlCu7 in as cast (T1) condition in Fig. 1.
Dark primary $\theta$-$\text{Al}_2\text{Cu}$ particles appear embedded in a bright $\alpha$-$\text{Al}$ matrix phase as a heterogeneous composite-like micro structure. Eutectic interconnected intermetallics between the $\alpha$-$\text{Al}$ dendrites are formed during non-equilibrium solidification of the casting.

Figure 1.: Light optical micrograph (LOM) of AlCu7 alloy in T1 condition.

2.2. Tensile test
Tensile testing was performed on a Zwick Z050 [12] with loading capacity of 0.1 kN to 20 kN. Cylindrical tensile test specimens were tested in B 6 x 30 shape accordingly to DIN 50125 (6 mm diameter, 30 mm initial gage length, threaded heads M10). The tests included loading-unloading cycles from defined load steps. The upper load in the first cycle was 70 MPa, followed by unloading to 10 MPa. For each following loading the load was increased by 20 MPa (to 90 MPa, 110 MPa, etc.), whereas the lower point of the resulting hysteresis loops was kept at 10 MPa. Load was measured by a load cell with 50 kN nominal load which meets the demands for accuracy class 0.5 (EN ISO 7500-1) in the range from 100 N to 50 kN. Elongation was measured by a contacting extensometer with accuracy class 0.5 accordingly to EN ISO 9513 in the measurement range from 0.02 to 50 mm.

2.3. Neutron diffraction
Neutron diffraction (ND) was performed with the angle dispersive strain scanner STRESS-SPEC [13] at FRM II research reactor in Garching, Germany [14]. A monochromatic particle beam with a wavelength of 1.67 Å was chosen accordingly to the lattice spacing (bent Si(400) double focusing monochromator unit). The high neutron flux of $2 - 3 \times 10^7$ n cm$^{-2}$s$^{-1}$ diffracted from the samples allowed short acquisition times ~ 7 min. The gage volume was set to 5 x 5 x 10 mm and a $\omega$-tilt of $\pm$ 5° (vertical rotation axis) to improve grain statistics sufficiently. The peaks were acquired with a position sensitive $^3\text{He}$ detector unit (PSD) covering an angle interval of $2\theta = [82°, 94°]$ for simultaneous detection of Al(311), Al(222), Al$_2$Cu(332) and Al$_2$Cu(422) Debye-Scherrer ring segments in 1.035 m distance and one acquisition (i.e. 7 min).

The in-situ tensile test rig [15] was mounted on the x, y, z - table of the diffractometer and aligned in the beam accordingly. Force was applied and strains were measured in load direction, in transmission through the tensile test specimens. Reference was taken in unloaded initial condition, neglecting any residual micro stresses from casting.
2.4. Synchrotron tomography

Synchrotron computed tomography (SCT) was carried out on the ID19 high energy imaging beam line at ESRF Grenoble [16]. A pink beam setup was used in parallel geometry with an energy maximum at ~ 19 keV. A primary beam aperture of 2 x 2 mm² flooded the Al-Cu samples completely. The samples were manufactured in cylindrical shape from the center-top regions of the tensile test specimens as used for neutron diffraction. A region of interest scan was made from the sample at a diameter of ~ 0.6 mm and length ~ 10 mm showing a representative volume of 0.7 x 0.7 x 0.7 µm³. Image acquisition was made in transmission behind the sample by a PCO edge camera (CMOS) with a sample-to-detector distance of 13 mm. Up to 6000 projections were acquired during one 365° scan within 7 min acquisition time [17]. Reconstruction was made by radon transformation, single distance phase retrieval and combined with motion correction filtering of ring artefacts resulting in a 3D tomography with a voxel size of (0.32 µm)³. Further data processing for visualization was made with the ImageJ software toolkit [18].

3. Results

A tensile test was performed on AlCu7 alloy in T1 condition to investigate the macroscopic elastic properties after cycling loads (Fig. 2). External load was applied until 70 MPa are reached then unloaded, again loaded to 90 MPa and unloaded increased by 20 MPa each and repeated until fracture at ~ 210 MPa.

![Figure 2.: Tensile test cycles of AlCu7 in T1 condition (left). Strain dependent Young's moduli evaluated by linear regression of the loading curve (right).](image)

The Young’s modulus was interpolated by linear regression curve at each loading step. The derived values are shown as a function of applied strain. The Young’s modulus starts with its highest value of 81.7 ± 3.3 GPa at 7 x 10⁻⁴ macroscopic strain and increasing strain (to 10 x 10⁻⁴, 13 x 10⁻⁴, 15 x 10⁻⁴, 18 x 10⁻⁴, 22 x 10⁻⁴ and 26 x 10⁻⁴) until fracture with its lowest value of 68.2 ± 1.9 GPa at 30 x 10⁻⁴ strain. The phase sensitive micro strains during tensile testing of AlCu7 are shown in Fig. 3 in Al(311), Al(222), Al₂Cu(332) and Al₂Cu(422) lattice planes under load at defined load steps until fracture. The externally applied load is transferred into lattice planes of the different phases weighted by their Young’s moduli and phase volume fractions. In the α-Al, load increases accordingly to linear Hooks law in an initially elastic region up to ~ 70 MPa. Above, the strain values split in between different Al lattice planes with higher value of 0.0023 in Al(311) and 0.0055 in Al(222) before fracture. The strains in Al₂Cu(332) and Al₂Cu(422) increase linearly in the beginning before 70 MPa and increases stronger (increasing slope) above. A saturation of micro strains can be observed after 150 MPa, staying constant (or even decrease) until fracture at ~ 200 MPa external loading. High resolution synchrotron tomography image slice of AlCu7 in T1 condition is shown in Fig. 3. A volume ~ 0.2 mm below the macroscopic fracture surface, in the tensile
test specimen is shown. External loading was applied until fracture vertically to the image slice. Al₂Cu appears bright in the grey α-Al matrix by absorption contrast imaging. The primary θ-Al₂Cu interconnected network appearing with a dark micro crack formed within a coral shaped eutectic region, perpendicular to external load direction.

Figure 3.: Phase sensitive micro strains in AlCu7 in T1 condition (left). Micro crack initiation perpendicular to external load direction within the heterogeneous micro structure (right).

4. Discussion
AlCu7 alloys consist of a heterogeneous micro structure of α-Al dendrites and eutectic θ-Al₂Cu in the inter-dendritic areas which are formed during casting (Fig. 1). This composite-like structure forms a brittle and stiff network of Al₂Cu eutectic interconnected reinforcement which is embedded in the ductile α matrix alloy. The mismatch in yield stresses (σ_y,α-Al ≈ 60 MPa vs. σ_y,Al₂Cu ≈ 150 MPa) and Young’s moduli (Eₐ-Al ≈ 70 GPa, Eₐ,Al₂Cu ≈ 100 GPa) are responsible for load partitioning of external stresses (macro to micro stresses) and plastic deformation within the heterogeneous micro structure. External stresses are distributed in between α and θ phase in an initially elastic region accordingly to the Young’s modulus and rule of mixture until 60 MPa is reached (Fig. 3). Above 60 MPa elasto-plastic matrix deformation can be observed at Al(311) and Al(222) which provokes loading of the θ phase, as observed in Al₂Cu(332) and Al₂Cu(422). As a result, high micro stresses at the α-θ interfaces induce localized plastic deformation in ductile α and crack initiation in brittle θ phase. Accumulated damage of the intermetallic reinforcement result in a permanent reduction of the Young’s modulus of AlCu7 alloys if cycling mechanical loads are applied (Fig. 2).

5. Conclusions
AlCu7 contains a composite-like micro structure which is responsible for its improved thermo-mechanical properties. The mismatch of elastic moduli between α and θ phase (ΔE ~ 30 GPa) generates elasto-plastic deformation in ductile α-Al and elastically deformed stiff, brittle θ-Al₂Cu until cracking. The resulting high micro stress gradients and interface shear stresses lead to crack initiation and damage accumulation in the brittle Al₂Cu. If mechanical loads exceeds α-Al yield strength cracking starts, which is partially bridged by plastic α matrix deformation, but influence the macroscopic mechanical properties i.e. degrade the Young’s modulus irreversibly. Therefore, the damage initiation and propagation mechanisms of composite-like cast alloys at small strains should be further investigated to be properly implemented in future calculation models and engine component construction to ensure operation under modified safe conditions.
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