3D investigation of damage during strain-controlled thermo-mechanical fatigue of cast Al-Si alloys

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Cast Al-Si alloys are used in automotive components like pistons due to their relatively high strength-to-weight ratio as well as excellent castability and heat conductivity. Particularly, the piston bowl rim in modern diesel engines must be able to withstand thermo-mechanical fatigue (TMF) conditions in a temperature range between RT-380 °C with thermal cycles of a few seconds during service [1]. The microstructure of cast Al-Si piston alloys consists of an α-Al matrix and interconnected 3D hybrid networks formed by eutectic/primary Si as well as Ni-, Cu-, Mg- and Fe-rich intermetallic phases. These networks play a decisive role on damage retardation of cast Al-Si alloys, as shown recently by the authors [2,3].

The TMF behaviour of Al-Si piston alloys with ~12 wt.% of Si and varying contents of Cu, Ni and Mg was investigated using the thermomechanical simulation system Gleeble. The temperature was cycled between 80-380°C keeping a constant strain of 0%. The cyclic stress evolution owing to the hindered extension and contraction of the alloys is shown Fig.1 (I) for one of the alloys investigated.

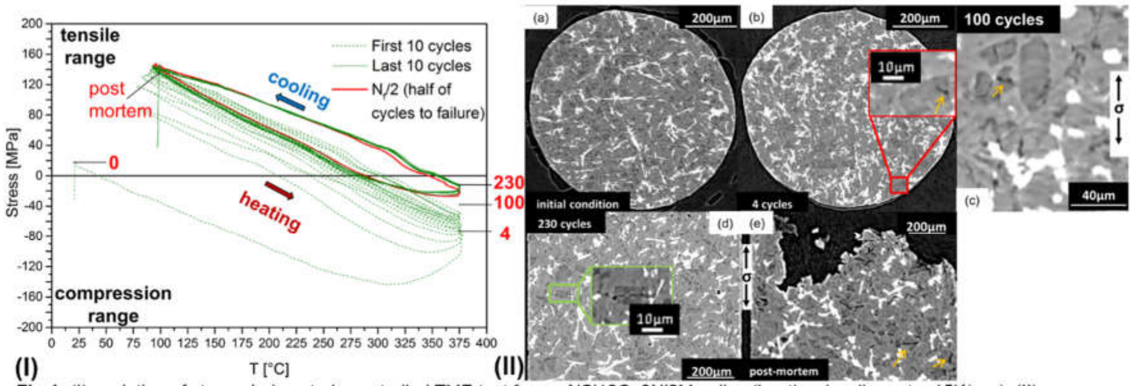

Fig.1: (I) evolution of stress during strain controlled TMF-test for an AlSi12Cu3Ni2Mg alloy (heating-/cooling rate: 15K/sec); (II) reconstructed 2D-slices after (a) 0, (b) 4, (c) 100, (d) 230 TMF-cycles and (e) after failure (375 cycles) of an AlSi12Cu3Ni2Mg alloy. TMF-loading is perpendicular to the plane of the figure in (a) & (b) and vertical to the plane of the figure (d) & (e); microstructure: bright aluminides, dark grey primary & eutectic Silicon, grey Al-matrix;

3D characterization of the microstructure and the damage evolution were conducted by synchrotron tomography experiments at the beamline P05 at DESY/Petra III in Hamburg for specimens after a selected number of thermal cycles. Image segmentation of the acquired in situ datasets was supported by a deep learning approach using convolutional neural networks [4]. Cracks through primary Si particles (Fig.1(II)) parallel to the sample length could be detected after 4 cycles and formation and accumulation of cracks oriented perpendicularly to the sample length could be observed with increasing number of TMF-cycles. Fig.2 shows a 3D Visualization of damage during TMF at selected cycle numbers until failure for the alloy depicted in Fig.1. Correlation between damage evolution and microstructural parameters indicate the influence of volume fraction, interconnectivity, interparticle distances of rigid phases, i.e. Si and intermetallics. Furthermore, the results obtained by the means of synchrotron tomography are complemented by neutron diffraction experiments on for the same selected cycle numbers as for the tomography in order to gain information about specific phase strains induced by TMF. Thermodynamic simulations provided further understanding on the impact of chemical composition on the formed microstructure and features affecting damage initiation, accumulation and retardation.

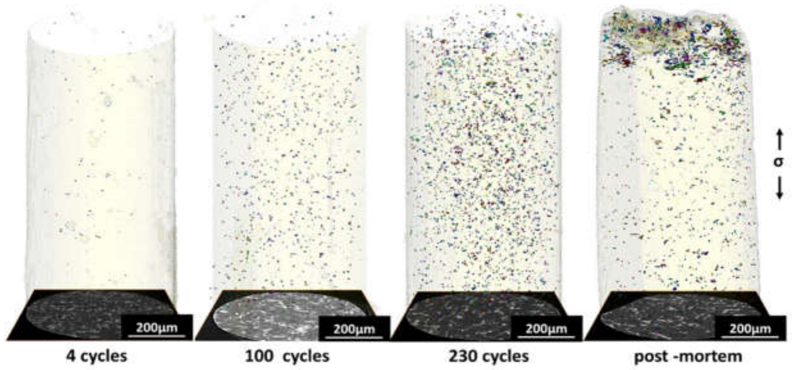

Fig.2: 3D Visualization of damage evolution at 4, 100, 230 cycles and after failure for an AlSi12Cu3Ni2Mg alloy (heating-/cooling rate: 15K/sec; TMF-loading is perpendicular to sample length.

References:

[1] The European Parliament and the Council of the European Union, Directive 2000/53/EC of the European Parlia the Council of 18 September 2000 on End-of-Life Vehicles, (2000), p. 34-42.
[2] K. Bugelnig et al., Mat. Sci. Eng. A 709 (2018), p. 193-202.
[3] K. Bugelnig et al., Materials 11(8) (2018), p. 1300.
[4] T. Strohmann et al., Scientific Reports 9 (2019), 19611, doi: 10.1038/s41598-019-56008-7.