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Damage mechanisms and evolution during thermomechanical fatigue of cast near eutectic Al-Si piston alloys

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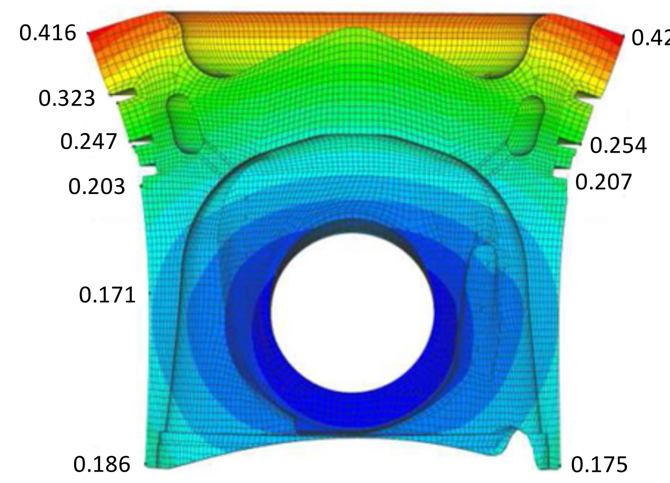
Motivation

Cast near eutectic Al-Si alloys are used in automotive pistons due to their 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 25 - 380 °C with thermal cycles of a few seconds during service. Topological and morphological changes in the microstructure owing to chemical compositions, thermal heat treatments and thermo-mechanical conditions during service can have a crucial effect on performance.
Damage mechanisms and evolution during TMF of two Al-Si piston alloys have been studied with regards to the effect of 3D microstructural features.



plastic deformation [mm] of the piston due to thermo-mechanical loading

Source: KS Kolbenschmidt GmbH

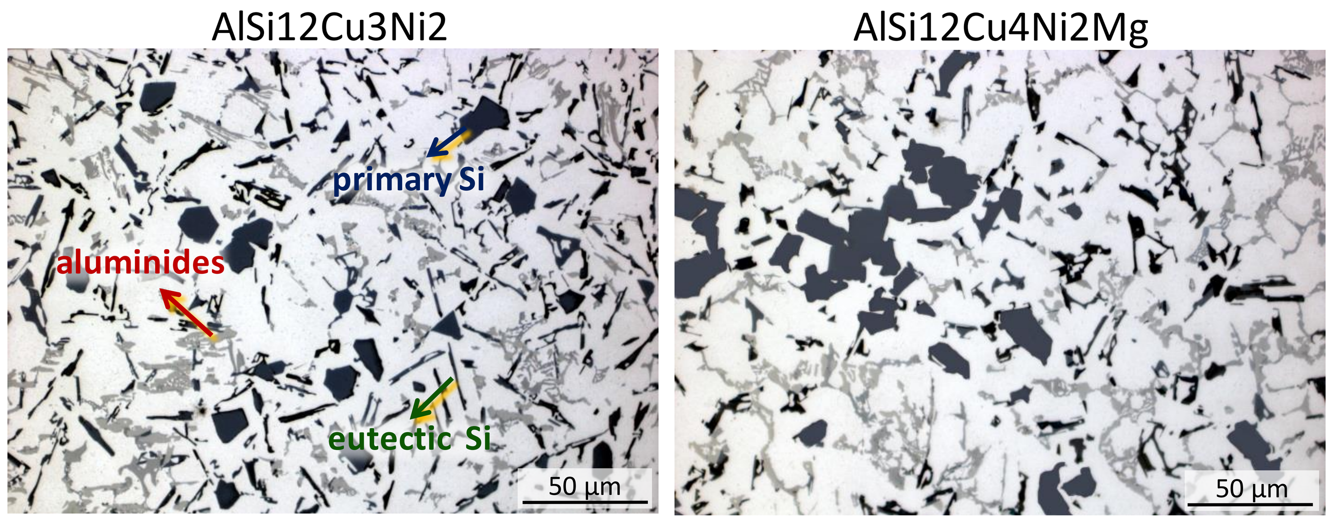
Materials

Alloy	Composition [wt.%]				
	Al	Si	Cu	Ni	Mg
AlSi12Cu3Ni2	bal.	~ 12	3	2	< 0.3
AlSi12Cu4Ni2Mg	bal.	~ 12	4	2	1

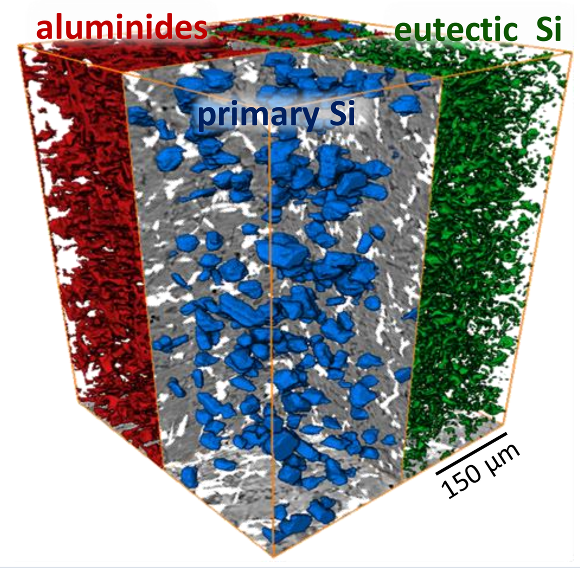
- gravity die casting
- heat treatment: T5

piston bowl rim area

Microstructure in initial condition

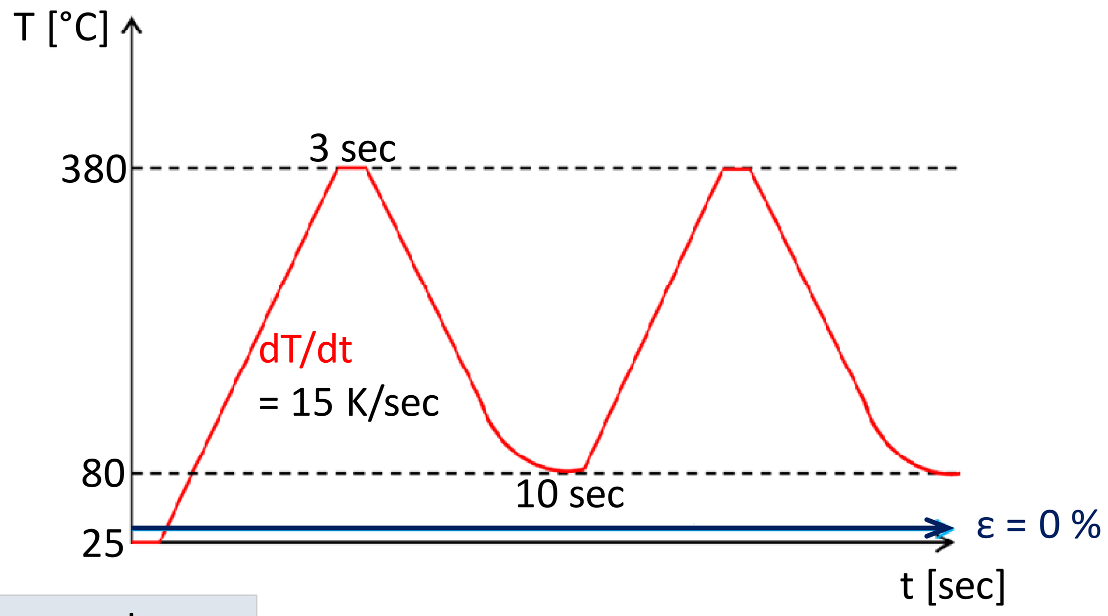


3D hybrid network of rigid phases

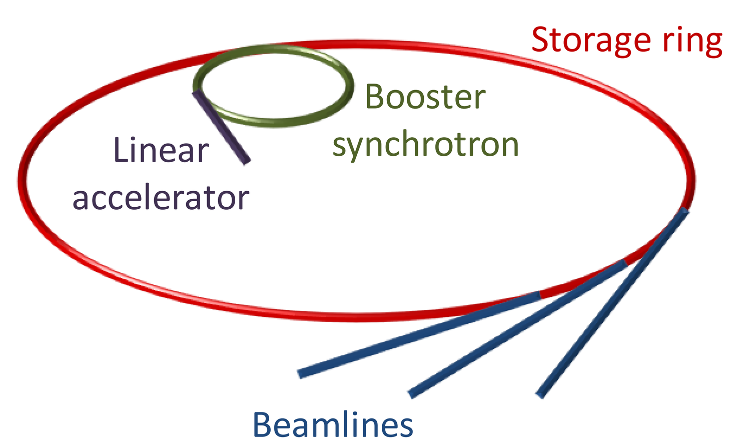


Methods

1. Gleeble 1500



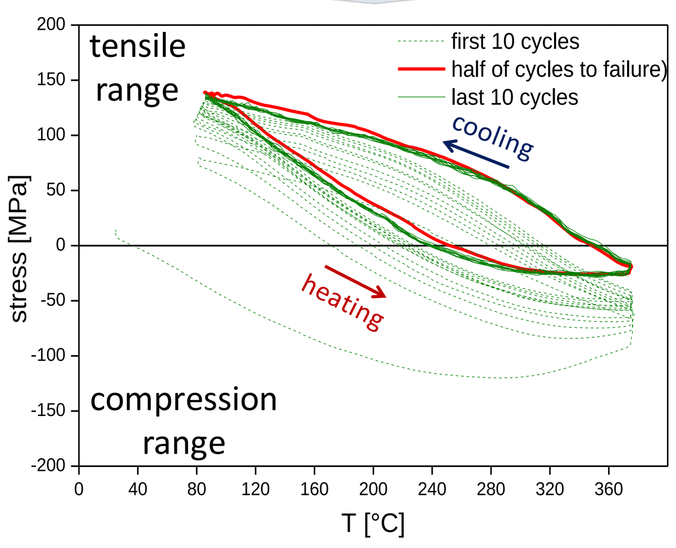
2. Synchrotron tomography



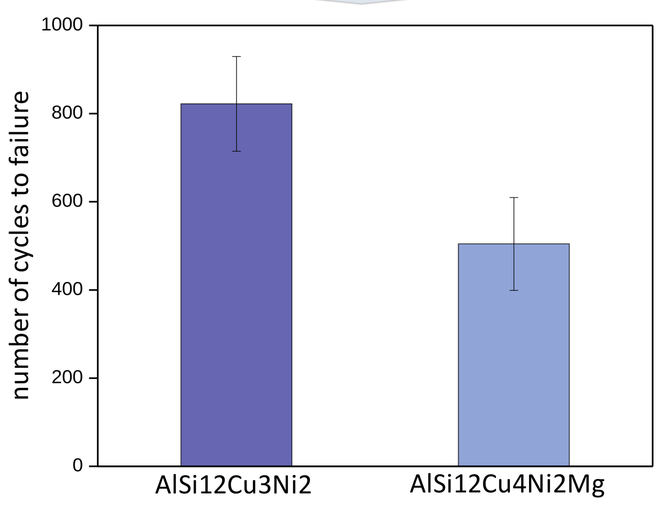
Parameters	Beamline P05	ID19
Energy [keV]	23	19
Voxel- Size [µm³]	$(1.18)^3$	$(0.33)^3$
Sample-to-detector distance [mm]	30	13
Exposure time [msec/proj]	1200	100
Nr. of proj.	900	5969
total scan time [h]	1.5	0.2

Results

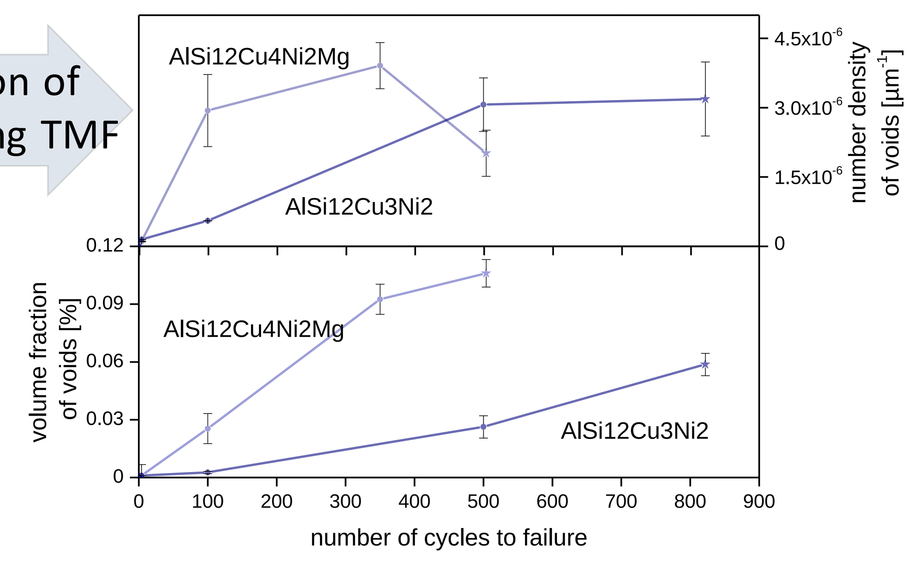
1. cyclic stress evolution during TMF



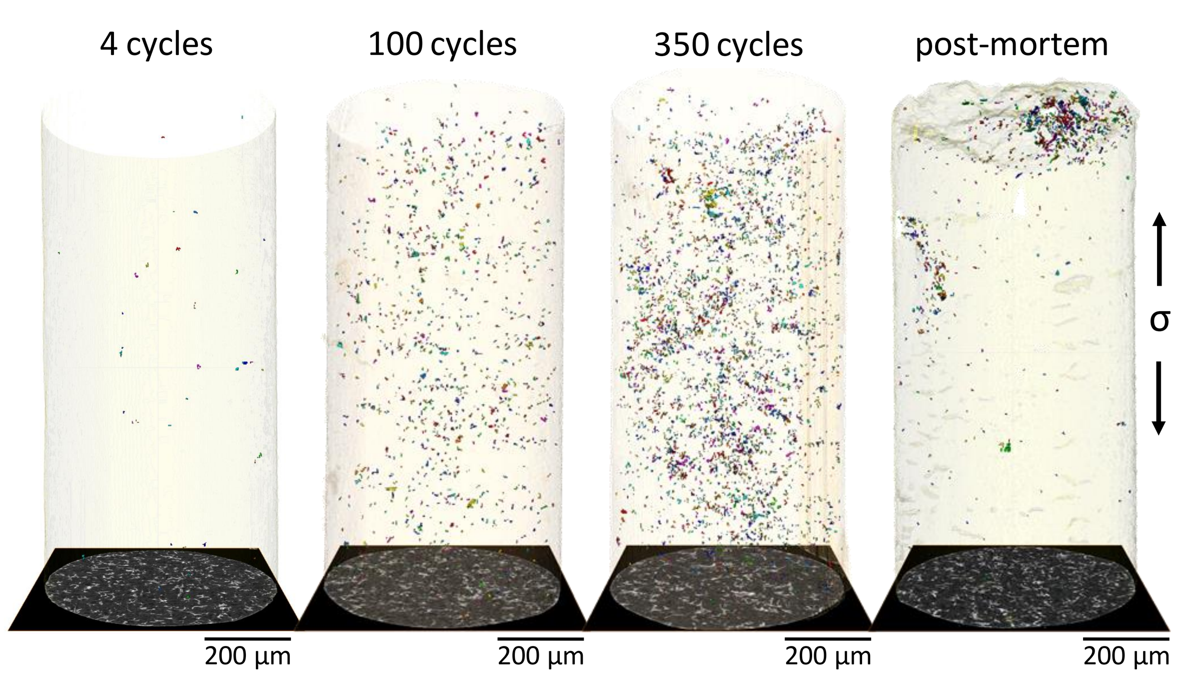
2. number of TMF-cycles to failure



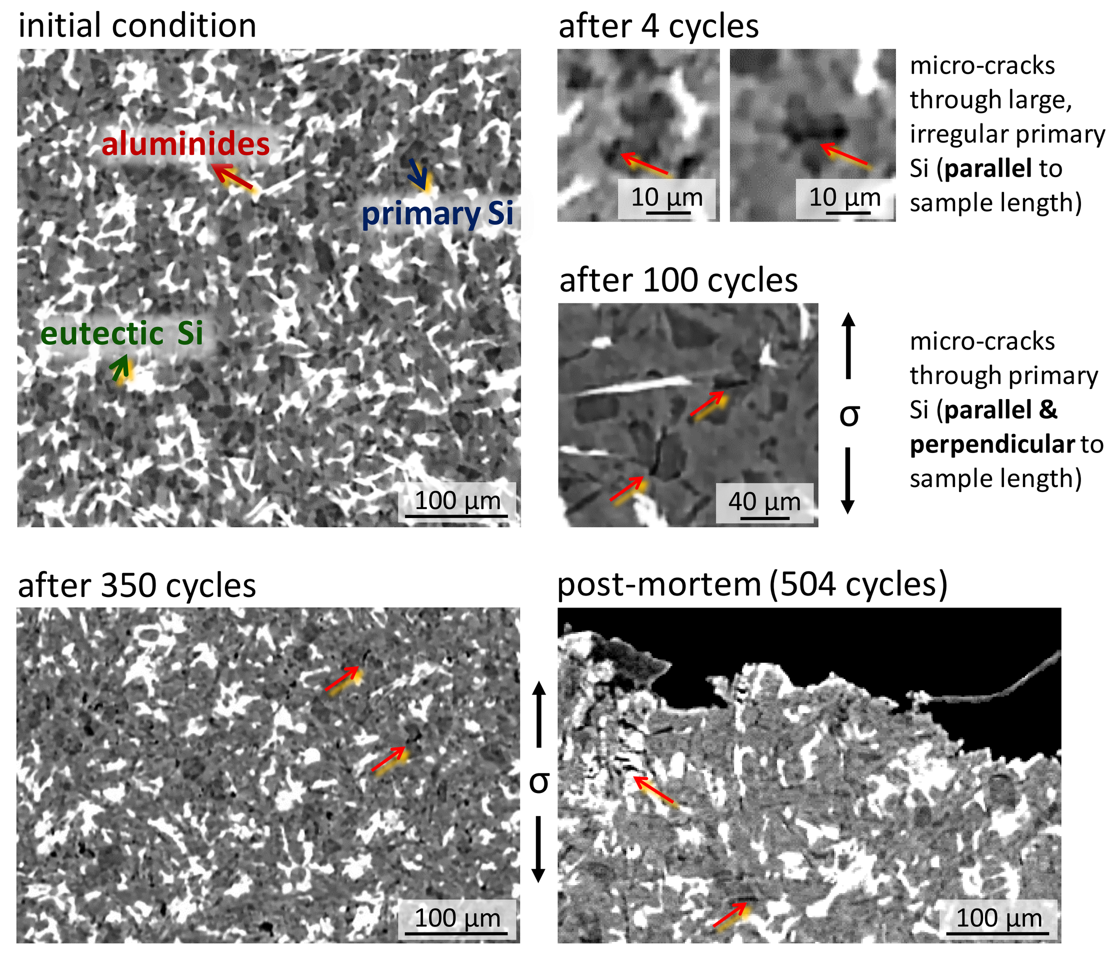
3. evaluation of damage during TMF



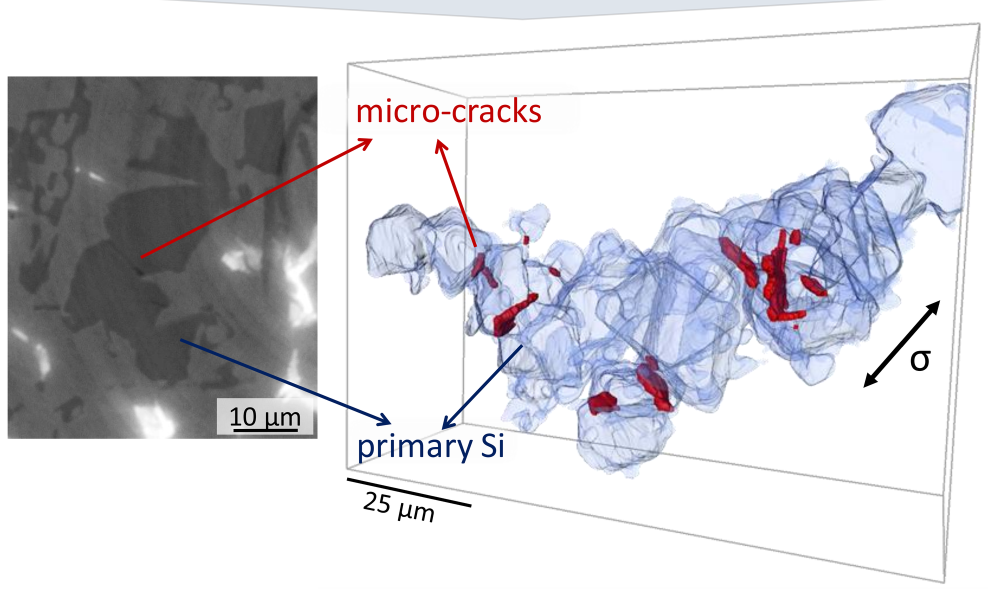
5. 3D visualization of damage evolution after selected TMF cycle numbers for AlSi12Cu4Ni2Mg



6. tomographic slices of the microstructure of AlSi12Cu4Ni2Mg after several TMF-cycles



4. Damage initiation preferentially in shape of micro-cracks **parallel** to sample length through large, irregular primary Si in clusters



Conclusions

- preferential damage initiation sites during TMF: micro-cracking through primary Si particles in Si clusters at junctions of coalesced primary Si particles
- after 4 thermal cycles: micro-cracks parallel to sample length due to compression stresses
- after 100 thermal cycles: cracks perpendicular to sample length due to tensile loading
- shortly before failure: further growth and accumulation of cracks preferentially perpendicular to sample length
- failure: main crack propagates along pre-existing damage and rigid phases

AlSi12Cu3Ni2

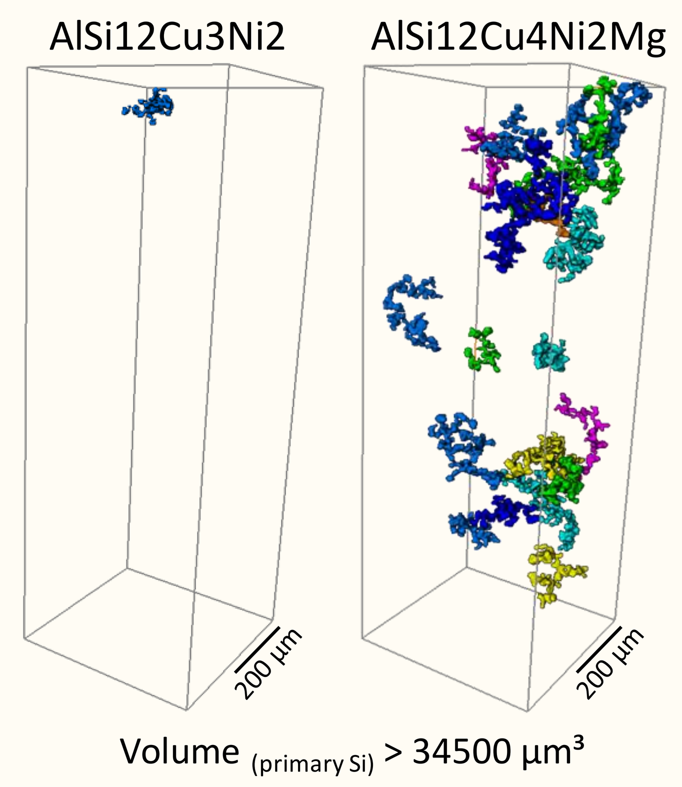
- high TMF resistance (822 ± 107 cycles)
- comparatively higher ductility and lower strength due to reduced Cu and Mg contents
- comparatively small homogeneously distributed primary Si particles (~ 8-10 µm)
- nearly no primary Si clusters present resulting in less sites for damage initiation and accumulation

AlSi12Cu4Ni2Mg

- lower TMF resistance (about 40%)
- lower ductility and higher strength due to high volume fraction of intermetallic phases
- larger primary Si particles (~ 10 - 15 µm)
- primary Si clusters provoke earlier formation and higher accumulation of damage in these regions

- High volume fractions of highly interconnected rigid phases can lead to a high tensile strength of the alloy at elevated temperatures, however the consequentially low ductility limits the TMF-resistance
- Closely packed primary Si and intermetallic phases facilitate crack formation and propagation
- more refined structures have a positive effect on the TMF resistance

Cu-rich alloy is prone to form large primary Si clusters during solidification



Volume $_{(primary\ Si)}$ > 34500 µm³

Acknowledgements

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