Thermomechanical Damage
From Microstructure to FE-Analysis

In the last years the increasing demands on engine efficiency and specific power have resulted in progressively higher loadings on internal components of combustion engines. Especially downsizing in gasoline and diesel engines has made thermomechanical lifetime a critical design issue. Therefore the durability assessment of such components is increasingly in demand, triggered by both reliability and economic requirements. The methodology developed at BMW power train for the fatigue assessment is with particular emphasis on the thermo-mechanical fatigue (TMF) aspect.

1 Introduction

The main thermo mechanical load is caused by cyclic temperature variations coming from the hot/cold cycles induced by the start-stop operation and the transient load variation during engine operation. The calculation of the cyclic temperature field is a complex task involving the use of computational fluid dynamic (CFD), conjugate heat transfer (CHT) and non-linear finite element (FE) analysis tools for the different components under consideration.

After a brief description of both the material and the CAE TMF process attention is given to the local damage evolution in aluminium silicon cylinder head alloys under thermo mechanical loading. Microstructural investigations in specimens as well as cylinder heads under engine loading are shown. Strain controlled TMF tests were carried out varying mechanical strain amplitudes and maximum temperature independently to identify the controlling mechanism for the damage evolution. The damage evolution is finally modelled with a Dowling type parameter based on the growth of micro-cracks.

2 Material Description

Cylinder heads of gasoline engines are produced in different casting technologies, using aluminium-silicon-copper (Al-Si-Cu) and aluminium-silicon-magnesium alloys (Al-Si-Mg). Besides their good castability they stand out for favourable thermo physical attributes and static properties like tensile strength and ductility, which can be influenced by a heat treatment in a large range. The dendrite structure constitutes of the primary aluminium matrix and the aluminium-silicon eutectic with different intermetallics, like Al_2Cu and AlMnFeSi phases, **Figure 1**. Aluminium-silicon alloys are primarily precipitation hardened. The mechanical properties and the fracture behaviour are directly connected to the microstructure. Coarse intermetallics and the eutectic silicon, as well as the porosity determine the fatigue and fracture behaviour [1].

3 TMF CAE Process

The analysis of TMF life of cylinder heads is a complex task, considering the differ-

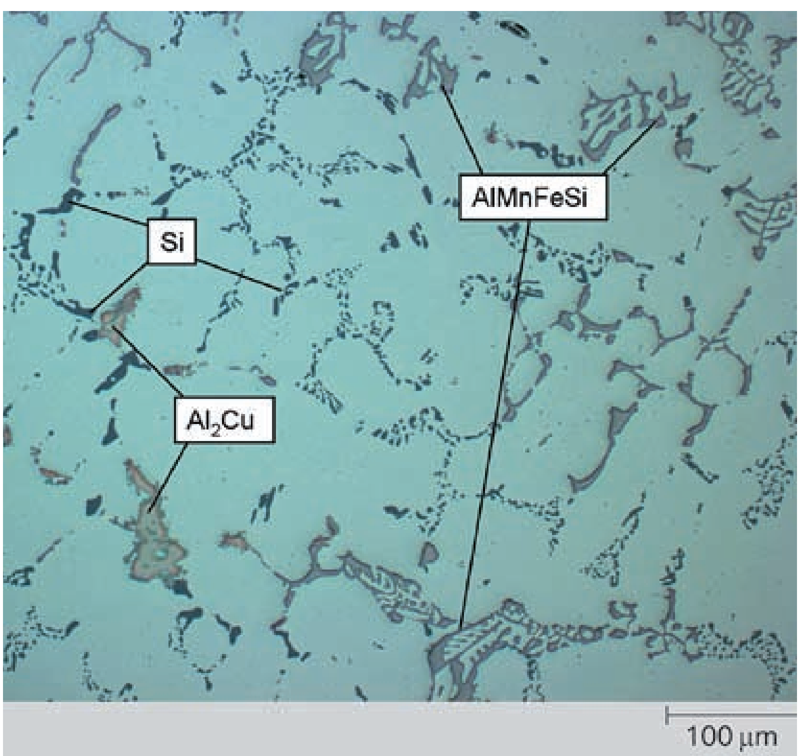

Figure 1: Microstructure of a secondary Aluminium-Silicon-Copper alloy

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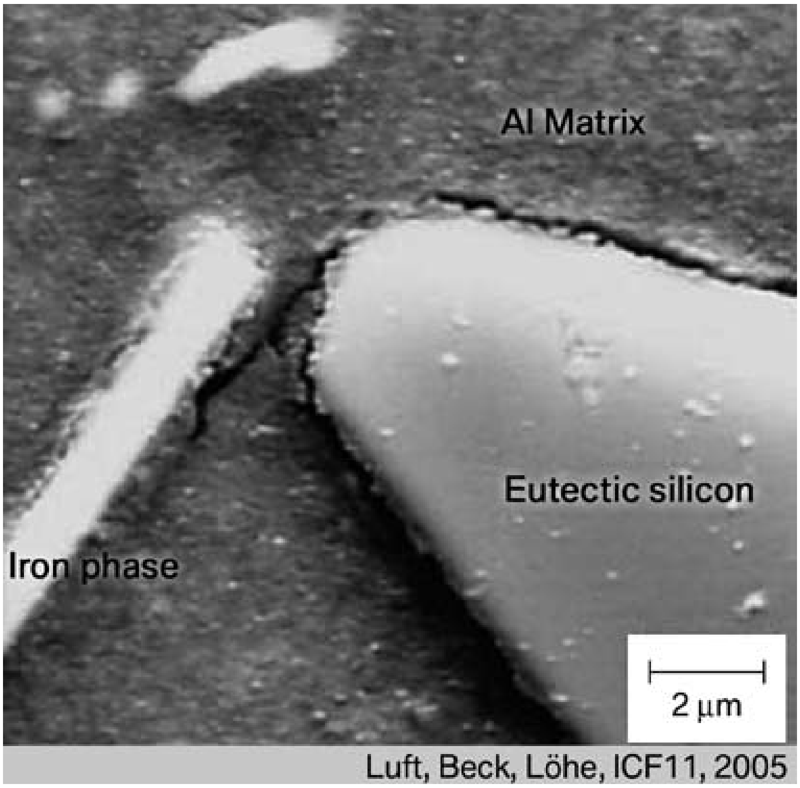

Figure 2: TMF crack initiation in an Aluminium Silicon alloy [6]

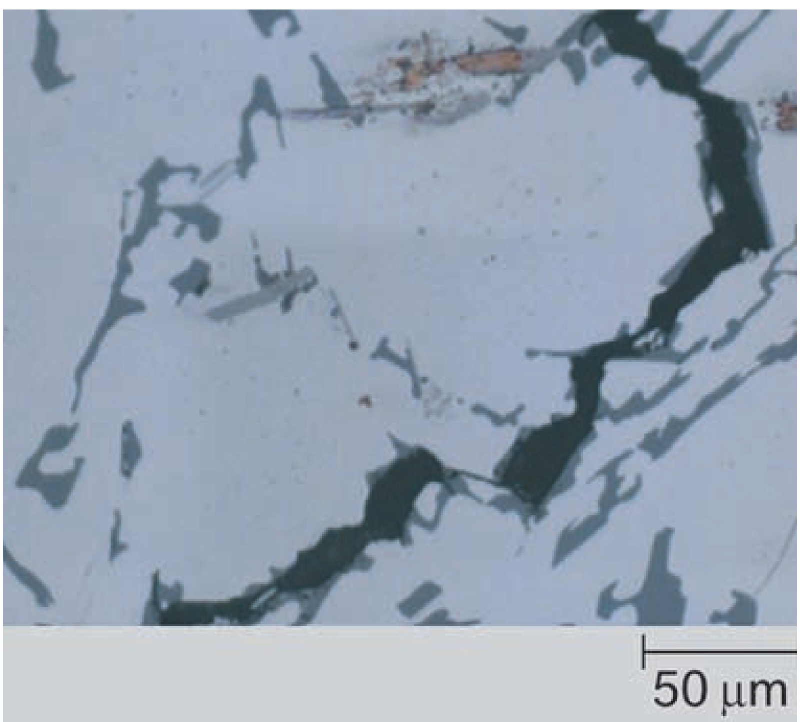

Figure 3: TMF crack path following brittle eutectic phases

ent steps involved in the calculation procedure. The thermo-mechanical fatigue problem originates from the cyclic thermal load. This load is calculated employing a software tool for the analysis of the gas exchange process, a tool for the three-dimensional simulation of combustion to get local heat transfer information, a tool for the CFD analysis of the water jacket and conjugated heat transfer analysis for the temperature field prediction in the fluid flow and structure. A non-linear FE code is used for the structural finite element analysis. The structural FE analysis includes the identification and application of the thermo-mechanical loading. As the calculated lifetime is very sensitive on the thermal load, the thermal model therefore is the key factor.

Aluminium shows the effect of ageing as well as viscous effects at the relevant operating temperatures. Depending on the alloy and heat treatment, different complexities of the constitutive model can be required. Alternative combinations of constitutive model and ageing model are used, ranging from elastic-plastic models with a nonlinear kinematic hardening to simple elasto-visco-plastic ones [2, 3, 4]. The change in yield strength by ageing may affect the nonlinear compliance redistribution in the component and therefore the resulting mechanical strain amplitude in critical areas.

For the cylinder head life assessment a damage parameter derived form the cyclic J-integral for the growth of microcracks is used. Initially Heitmann [5] defined this parameter for the use with steels. This parameter is composed of a plastic and an elastic part and was adapted for the use with aluminium-silicon alloys [2].

4 Experimental Details

TMF-tests were performed in an electromechanical testing machine. To reach the required cooling and heating rate of 10 K/s, a 5 kW inductive heater and forced air cooling was used. The strain was measured with a capacitive extensometer. The force was determined with a 100 kN load cell and the temperature was measured with a Ni-CrNi ribbon-type thermocouple. At the beginning of each test, the thermal strain ε_{th} of the specimen as a function of temperature was determined by reference temperature cycles at zero force. Afterwards, the machine was switched to strain control and the total strain ε_t was controlled in such

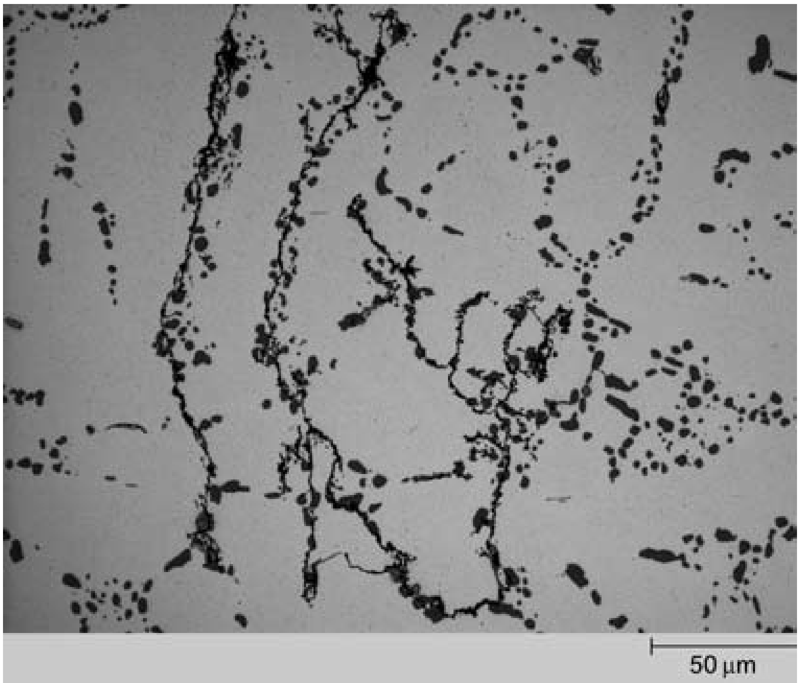

Figure 4: TMF crack initiation in a cylinder head

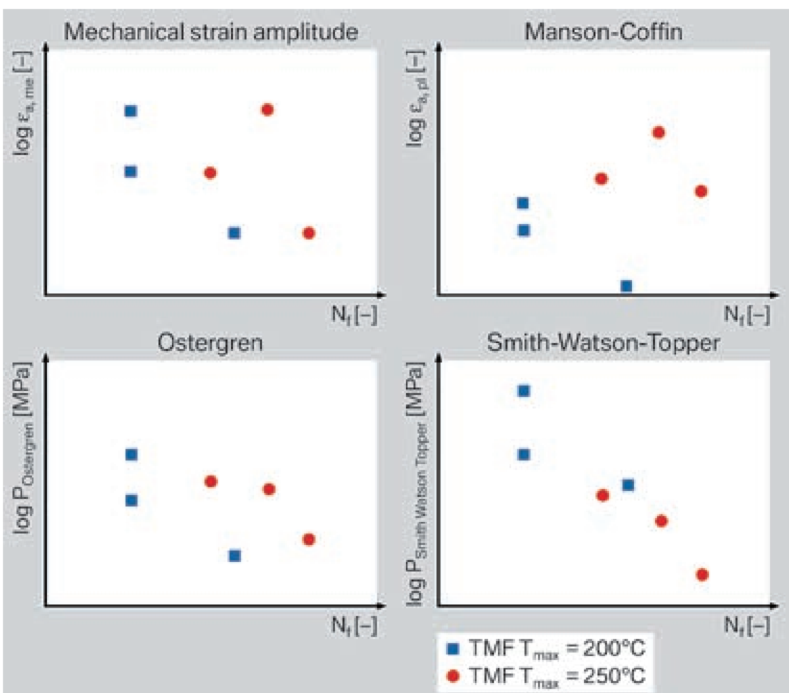

Figure 5: Mechanical and plastic strain amplitudes, Smith-Watson Topper and Ostergren parameters versus the number of cycles to failure for TMF experiments varying temperature and mechanical strain independently

a way that the total mechanical strain ε_{tme} is phase shifted by 180° against the thermal strain, according to the relationship $\varepsilon_t = \varepsilon_{t,me} + \varepsilon_{th}$. A set of TMF-tests on an Al-Si-Cu alloy was performed to determine the influence of the total mechanical strain amplitude and the maximum temperature (T_{max}) of the TMF-cycles on the lifetime-behaviour, while all other test parameters remain constant. These experiments were conducted at T_{max} = 200 °C and 250 °C and a dwell time at maximum temperature (t_d) of 60 s. Starting with $\varepsilon_{t,me}$ = 0 at T_{min} = 50 °C. The mechanical strain amplitude was varryied up to $\varepsilon_{a,tme}$ = 0,5 % independently of temperature.

5 Damage Evolution in Aluminium-silicon Alloys

In recent years the microstructural damage evolution in Aluminium-Silicon alloys was investigated in a series of research programs at the University of Karlsruhe [7, 8, 9]. Under TMF conditions distinct plastic deformation, caused by the TMF-load, results in crack initiation due to a separation of silicon particles from the aluminium matrix early compared to the macroscopic observed lifetime, **Figure 2**. The separation is a result of the significant unequal thermal expansion coefficient of aluminium and silicon, which leads to stressing of the interface with each thermal cycle and therefore to a separation during thermal loading. The following crack-propagation mainly occurs along brittle phases in the eutectic structure, **Figure 3**.

Figure 4 shows the microstructural damage evolution in a cylinder head. The cylinder head was run in a thermal shock engine test and showed signs of plastic deformation in the intervalve region, but no macroscopic crack initiation. Detailed metallographic investigations revealed initiated cracks on the microscopic scale even well below the surface. The observed crack initiation sites and propagation schemes are comparable to the observed damage in the TMF experiments.

6 Description of Damage

The results of the different TMF-test parameters on the observed fatigue life are given in **Figure 5**. Diagrams for mechanical and plastic strain amplitude, Smith-Watson Topper and Ostergren parameters versus the number of cycles to failure are shown. The rise of Tmax from 200 °C to 250 °C leads to an increase in lifetime for all strain amplitudes. Therefore a description of lifetime just by use

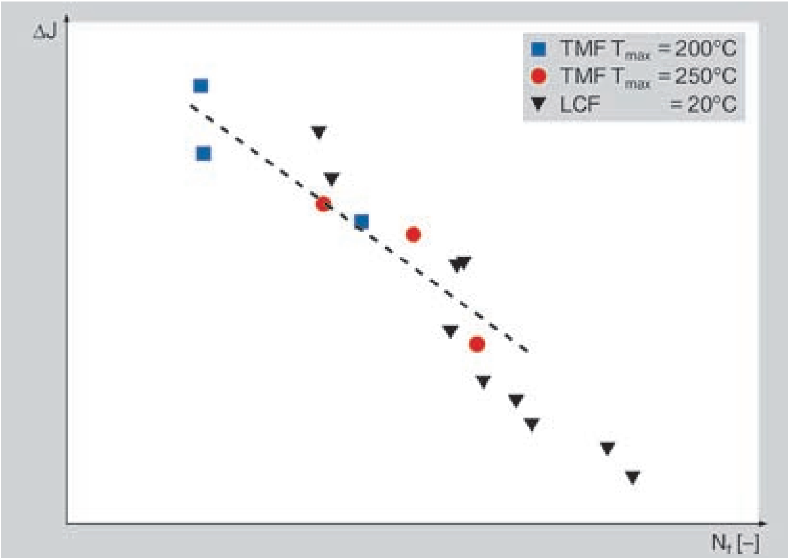

Figure 6: TMF and LCF tests

of the mechanical and plastic strain amplitude is not possible. Due to the poor correlation the use of the Ostergren parameter in the form of

$$P_{OST} = \sigma_{MAX}\varepsilon_{a,pl} \qquad \text{Eq. (1)}$$

as an approximation for the dissipated energy allows no description of lifetime, as can be seen in Figure 5. The Smith-Watson-Topper parameter shows the best correlation with lifetime. This indicates a strong dependency of damage evolution in aluminium-silicon alloys on the macroscopic maximum induced stresses, viz. strain energy density. The parameter of Smith-Watson-Topper is used in the following form:

$$P_{SWT} = \sigma_{MAX}\varepsilon_{a,me} \qquad \text{Eq. (2)}$$

In these relations $\varepsilon_{a,me}$, $\varepsilon_{a,pl}$ and σ_{MAX} are the mechanical, plastic strain amplitudes and the maximum stress of the cycle respectively.

Based on this observation the dependency of fatigue life was modelled by adapting a energy parameter for the cyclic J integral like proposed by Dowling in [10].

$$\Delta J = f_1 W_e + W_p \qquad \text{Eq. (3)}$$

The elastic energy was calculated as

$$W_e = \frac{\sigma^2_{max}}{2E} \qquad \text{Eq. (4)}$$

In [11] the dissipated energy per cycle is proposed to describe the lifetime behaviour, it is calculated in our case as

$$W_p = \int \sigma \cdot \& \, dt \qquad \text{Eq. (5)}$$

where We and Wp are the elastic and plastic energy, E the Young's modulus and f1 a material constant. The parameter allows describing the lifetime dependency of the TMF experiments, as well as the lifetime of isothermal Low cycle fatigue experiments at room temperature, **Figure 6**. This indicates that the combination of dissipated plastic energy and induced stress is responsible for both lifetime dependencies. The complex interaction of ageing, temperature, crack initiation and crack growth will require questioning the applicability of the deformation and damage model in each case for aluminium-silicon alloys.

7 Conclusion

The observed micro crack initiation in cylinder heads is of the same type as the observed damage in the TMF specimens. The study of the effect of maximum temperature and mechanical strain amplitude showed the strain energy density and the maximum induced stresses as the controlling factors on TMF fatigue life in the investigated Al-Si-Cu alloy. The resulting damage modelling confirms the already applied cyclic J-integral damage concept. Applied in engine projects the adapted energetic Heitmann parameter showed a good quality of its predictive capabilities.

References

[1] Thalmair, S.; Fischersworring-Bunk, A.; Klinkenberg, F-J.; Lang, K.-H.; Löhe, D.: Materialprüfung, 49, 2007, 113-117

[2] Thalmair, S. Fischersworring-Bunk, A. Thiele, J. Ehart, R. Guillou, M.: SAE World Congress 2006, Detroit, USA, April 3-6, 2006-01-0541, 2006

[3] Thalmair, S.; Fischersworring-Bunk, A.; Lang, K.; Löhe, D.: Proc. Intl. Fatigue Conf. 2006, Atlanta, USA, 14-19 May, 2006

[4] Ehart, R.; Nefischer, P.; Riedler, M.: Betriebsfestigkeit in der virtuellen Produktentwicklung, Steyr, Oct. 11.-12., 33. Tagung DVM-Arbeitskreis Betriebsfestigkeit, 2006

[5] Heitmann, H.H.; Vehoff, H.; Neumann, P.: 6th Int. Conf. on Fracture, 1984

[6] Luft, J.; Beck, T.; Löhe, D.: 11th Int. Conf. on Fracture, Turin, Italy, March 20-25, 2005

[7] Flaig, B.: Isothermes und thermisch-mechanisches Ermüdungsverhalten von GK-AlSi10Mg wa, GK-AlSi12CuMgNi und GK-AlSi6Cu4, PhD thesis, Universität Karlsruhe (TH), 1995

[8] Luft, J.; Beck, T.: Weiterentwicklung des Al-Leichtbaus für motorische Hochleistungskomponenten mit Hilfe einer neuen TMF/HCF Methode, BMBF Verbundprojekt 03N3095, Universität Karlsruhe (TH), 2005

[9] Henne, I.: Schädigungsverhalten von Aluminiumgusslegierungen bei TMF und TMF/HCF-Beanspruchung, PhD thesis, Universität Karlsruhe (TH), 2006

[10] Dowling, N.E.: Journal of Materials, 7, 1972, 71-87

[11] Charkaluk, E.; Bignonnet, A.M.; Constantinescu, A.; Dang Van, K.: Fatigue Fract. Engng. Mater. Struct., 25, 1199-1206

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