LIFETIME AND DAMAGE BEHAVIOUR OF A CAST ALUMINIUM ALLOY UNDER TMF AND SUPERIMPOSED TMF/HCF LOADING

J. LUFT, T. BECK, D. LÖHE
Institut für Werkstoffkunde I, University of Karlsruhe, Germany

ABSTRACT

This present paper describes the thermal-mechanical fatigue (TMF) and the superimposed thermal-mechanical fatigue/high cycle fatigue (TMF/HCF) behaviour of an Al-7Si-0.3Mg cast alloy. The alloy is widely used for cylinderheads of automobile engines. Repeated start-stop cycles cause thermal cycling in the engine material, whereas combustion-pressures cause a superimposed mechanical high-cycle fatigue loading. This study aims to characterise the cyclic stress-strain behaviour of this alloy as well as the lifetime for TMF and TMF/HCF-loading. Another aim is to clarify the fracture-processes dominating for TMF and TMF/HCF-loading.

The influence of different maximum temperatures for pure TMF-loadings and the significant decrease of lifetime as a consequence of applying superimposed TMF/HCF-loading compared to pure TMF-tests, as soon as the HCF-amplitude exceeds a certain value, is demonstrated. Furthermore, the effect of an increased HCF-frequency to the lifetime for TMF/HCF-loadings is examined. The results show a decreasing influence of the superimposed HCF-frequency with a decreasing superimposed HCF-amplitude.

Furtheron, microstructural examinations show the crack initiation caused by pure TMF-loading due to the distinct plastic deformation, which results in a seapration of eutectic silicon particles from the α-aluminium matrix in an early stage of loading. Increasing superimposed HCF-loadings result in an increasingly pronounced formation of slip bands, which lead to an accelerated crack propagation along slip bands within the α-aluminium matrix as well as in the eutectical zones.

1 INTRODUCTION

Cast Al-Si-Mg alloys are generally used for cylinderheads of automotive engines. The permanently growing efforts to increase the efficiency, power density and to reduce the emission result in an increase of the combustion pressure and –temperature and therefore in the need for a further development of the used materials. The TMF-loadings in an engine-part arise due to temperature gradients: Repeated start-stop cycles cause temporal and local inhomogeneous temperature ranges, which lead to low-frequency TMF-loading. Simultaneously, high-frequency mechanical loading arises from cyclic compression- and mass-forces. This HCF-loading is superimposed to the TMF-loading. Additionally, caused by the high service temperatures, precipitation hardened alloys are affected by overageing, resulting in a significant decrease of strength with continuing service. As a result of an increase of these thermal-mechanical loadings, there is the need to determine the load limit of the used alloys under these service conditions as exactly as possible. Furthermore, to reduce the time-to-market period and the financial efforts of developing a combustion engine, material testing methods have to simulate the complex loadings mentioned above as close as possible to the actual conditions in service. Based on the resulting material data, a quantitative forecast of the lifetime of combustion engine components will be possible. As previous research work figured out, isothermal tests can not reach this demand [1,2].
The present paper gives results of Out-of-Phase (OP)-TMF-tests and OP-TMF-tests with superimposed mechanical HCF-loading at the cast aluminium alloy Al-7Si-0.3Mg. The results are interpreted on the basis of stress-strain curves, S-N-curves and metallographic examinations.

2 EXPERIMENTAL DETAILS

All tests were conducted on the cylinderhead alloy Al-7Si-0,3Mg in the peak hardened state (T6). The heat treatment conditions are: annealing for 5h at 525°C, quenching in water and ageing at 160°C for 8h. The chemical compositon of the alloy is listed in Table 1.

Table 1: Chemical composition in wt.%

	Si	Mg	Cu	Zn	Fe	Ni	Ti	Sn	Mn	Sr
AlSi7Mg	7.382	0.323	0.01	0.014	0.105	0.014	0.138	0.004	0.006	0.02

The used specimen had a solid cylindrical geometry with a length over all of 115mm and a diameter of 12mm. The parallel length was 17mm with a diameter of 7mm. The microstructure in the as-received state is given in Figure 2.

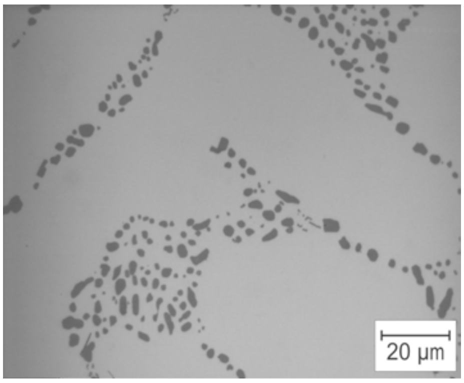

Figure 2: Microstructure of Al-7Si-0,3Mg in the T6 state

TMF-tests were performed in an electro-mechanical testing machine. For the superimposed TMF/HCF-tests, a servo-hydraulic fatique testing machine was used. To reach the required cooling and heating rate of 10 K/s, a 5KW inductive heater and forced air cooling was used. The strain was measured with a capacitive extensometer. The force was determined with a 100KN 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 five reference temperature cycles at zero force. Afterwards, the machine was switched to strain control and the total strain ε_t was, according to the relationship $\varepsilon_t = \varepsilon_t^{me} + \varepsilon^{th}$, controlled in such a way that the total mechanical strain ε_t^{me} was phase shifted by 180° against the thermal strain – time path with a defined ratio of $\varepsilon_{a,t}^{me} / \varepsilon_a^{th}$.
A first set of TMF-tests was performed to determine the influence of the maximum temperature (T_{max}) of the TMF-cycles on the cyclic deformation- and the lifetime-behaviour, while all other test parameters were constant. These experiments were conducted at T_{max}=250°C, 275°C and 300°C and a dwell time at maximum temperature (t_d) of 120s. Starting with ε_t^{me}=0 at T_{min}=50°C, the thermal expansion was completely suppressed throughout the TMF-cycle (Out of phase-

loading; R_ε=-∞). The ultimate number of cycles was generally 10^4. In a second set of TMF-tests, the influence of the total mechanical strain amplitude on the cyclic deformation- and lifetime-behaviour was investigated. During these tests, different mechanical loadings between $1<\varepsilon_{a,t}^{me}/\varepsilon_t^{th}<2$ at a constant maximum temperature of 250°C were applied. All other test parameters were the same as in the first test set.
To determine the influence of an additional superimposed mechanical high cycle fatigue (HCF) loading, a set of TMF-test with $\varepsilon_{a,t}^{me}=\varepsilon_a^{th}$, T_{max}=250°C and a dwell time of 120s at T_{max} was performed with a superimposed strain controlled HCF-loading with a frequency of 6,25Hz. This frequency was chosen to get 1000 HCF-cycles within one TMF-cycle. The applied ranges of the superimposed HCF-loading were $\varepsilon_{a,t}^{me}$(HCF)=0.02% up to 0.1%. To examine the influence of an increased frequency of the HCF-loading, another superimposed TMF/HCF-test set with f(HCF)=18,75Hz was conducted. All other test parameters were the same as in the other TMF/HCF-test set.

3 RESULTS AND DISCUSSION

The hysteresis loops of the nominal stress (σ_n) versus the total mechanical strain (ε_t^{me}) resulting from TMF loading with $\varepsilon_{a,t}^{me}=\varepsilon_a^{th}$ and t_d = 120s at T_{max}=250°C up to 300°C at $N=N_f/2$ are shown in Figure 3. With increasing maximum temperature, the plastic strain range increases due to the increasing total strain range and decreasing yield strength because of overageing. Without considering the effect of overageing, the increasing compressive plastic deformation during heating up should lead to increasing mean stresses with increasing T_{max}. However, overageing, which is also enhanced when T_{max} is risen, results at the same time in a decreasing resistance against plastic deformation also at temperatures near T_{min}. Therefore, with increasing T_{max}, a decrease in σ_{max} and σ_m occurs [1,2,3] . Due to the distinctive overaging for t_d=120s at the applied maximum temperatures and $N=N_f/2$, which results in an pronounced softening of the material, Figure 3 shows at all applied T_{max} nearly identic values for σ_{max} and σ_{min}.

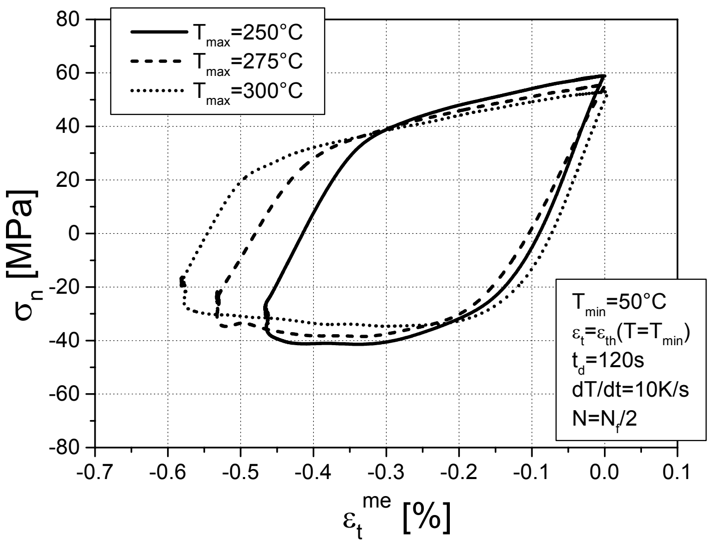

Figure 3: First TMF-set – Hysteresis loops at $N=N_f/2$

The stress-strain paths of the experiments in Figure 3 show a large, nearly horizontal segment within the heating phase of the cycles, indicating a strong influence of creep to the deformation process. During the dwell time at T_{max}, distinctive stress relaxation for all T_{max} can be observed, which results in a decrease of the compressive stress by about 15 MPa at all T_{max}.
The σ_{max}-lgN-paths (Figure 4) show at T_{max}=275°C and 300°C a continuous decrease of σ_{max} from the first cycle, whereas at T_{max}=250°C the decrease of σ_{max} begins at N=10. The maximum stress at N=1 for T_{max}=300°C is lower than at T_{max}<300°C due to the fact that before starting a TMF-test, 5 reference cycles are conducted without a mechanical load to determine the thermal strain as a function of temperature (see section 2).
This results in increasing overageing with increasing T_{max} before the strain controlled TMF tests is started and hence in a decreased maximum stress for N=1. The σ_{min}-lgN-paths are also influenced by that fact and show therefore with increasing T_{max} a decrease of $|\sigma_{min}|$ up from N=1.
The σ_m-lgN-path describes a sharp increase within the first cycles, especially at T_{max}=275°C and 300°C due to extensive compressive plastic deformation during heating up and the dwell time. The subsequent continuous decrease of σ_m is a consequence of the decreased maximum stress caused by the softening of the material as described above.

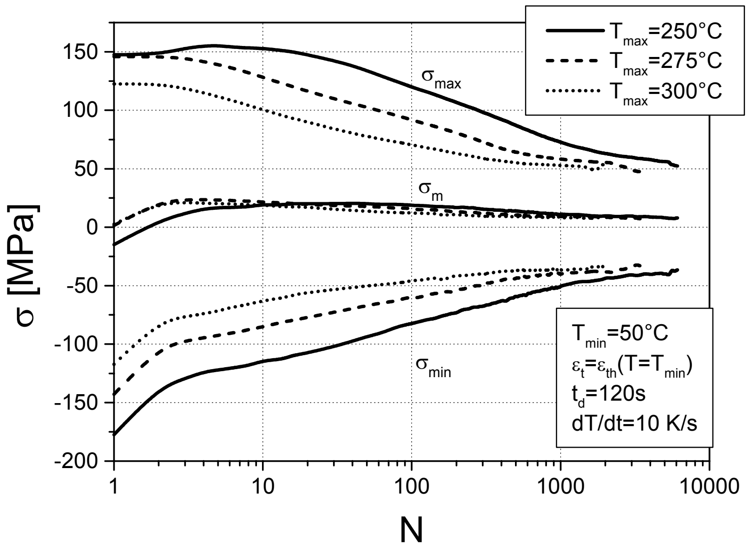

Figure 4: First TMF set – σ_{max}-lgN-, σ_m-lgN- and σ_{min}-lgN-paths at different T_{max}

The influence of different TMF-test parameters and superimposed HCF-loadings on the lifetime behaviour is provided by an $\varepsilon_{a,t}^{me}$-lgN-graph (Figure 5). In this graph $\varepsilon_{a,t}^{me}$ is the sum of the strain amplitudes of both, the TMF- ($\varepsilon_{a,t}^{me}$(TMF)) and the HCF- ($\varepsilon_{a,t}^{me}$(HCF)) loadings. The regression-line derived from the squares describes the results of the TMF-tests with $\varepsilon_{a,t}^{me}=\varepsilon_a^{th}$ for different maximum temperatures of T_{max}=250°C, 275°C and 300°C. The round symbols describe the lifetime behaviour of TMF-tests with $\varepsilon_{a,t}^{me}/\varepsilon_a^{th}>1$ and a constant T_{max} of 250°C.
The TMF-lifetime with an increased load and a constant maximum temperature ($\varepsilon_{a,t}^{me}/\varepsilon_a^{th}>1$, T_{max}=250°C) is significantly extended in comparison to TMF-tests with different maximum temperatures and according to $\varepsilon_{a,t}^{me}=\varepsilon_a^{th}$, with an increased mechanical load with raising T_{max}. For

both TMF-test sets with sections of identical mechanical loadings ($\varepsilon_{a,t}^{me}$(TMF)) , the negative influence of an increased temperature to the lifetime becomes visible.

The comparison of superimposed TMF/HCF-tests at T_{max}=250°C (triangles) and TMF-test with $\varepsilon_{a,t}^{me}/\varepsilon_a^{th}>1$ at T_{max}=250°C (circels) results in a strong influence of the mechanical HCF-amplitude beyond a value of $\varepsilon_{a,t}^{me}$(HCF)=0,02%, but up to $\varepsilon_{a,t}^{me}$(HCF)=0,02% no difference in lifetime occurs. The implication of the lifetimes for TMF- and TMF/HCF-test sets is an existence of a threshold at $\varepsilon_{a,t}^{me}$(HCF)=0,02%, which lead to an identical N_f of superimposed TMF/HCF-tests and TMF-tests with $\varepsilon_{a,t}^{me}/\varepsilon_a^{th}>1$ up to this value.
The lifetime behaviour of superimposed TMF/HCF-tests with f(HCF)=18,75Hz (diamonds) confirm the existence of a threshold at $\varepsilon_{a,t}^{me}$(HCF)=0,02%. The influence of a raised HCF-frequency decreases with decreasing HCF-amplitudes and lead to an identical lifetime behaviour at $\varepsilon_{a,t}^{me}$(HCF)=0,02% for TMF/HCF-tests with f(HCF)=6,25Hz and TMF/HCF-test with f(HCF)=18,75Hz. With increasing superimposed HCF-amplitudes the influence of the HCF-frequency increases and results in a stronger decrease of lifetime.

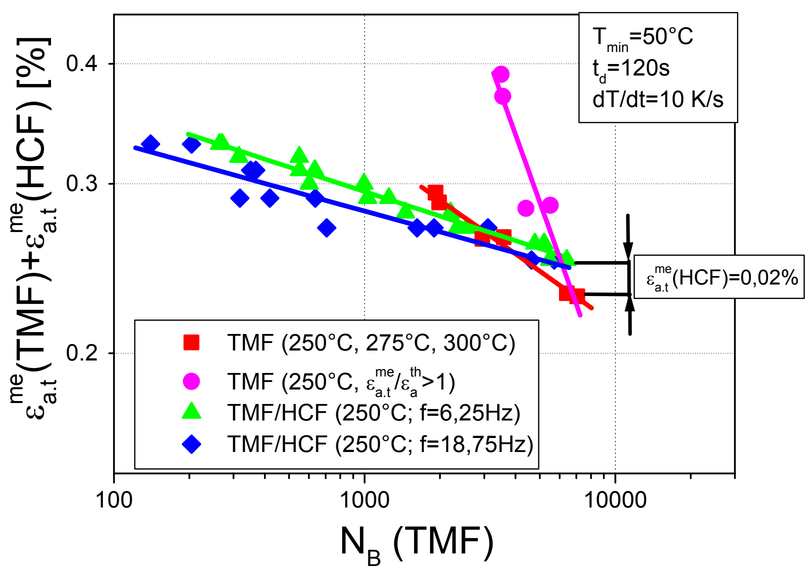

Figure 5: $\varepsilon_{a,t}^{me}$ –lgN-graph for TMF- and superimposed TMF/HCF- loading

Results of superimposed TMF/HCF-tests point out a significant decrease of fatigue life compared to pure TMF-tests after exceeding a certain value of the superimposed HCF-amplitude. The distinct plastic deformation, caused by the TMF-load, results in a crack initiation due to a seapration of silicon particles within the aluminium matrix in an early stage of loading (Figure 6). The separation is a result of the keen unequal thermal expansion coefficient of aluminium and silicon, which lead to a shift of the interface and therefore to a separation during thermal loading. Subsequent to the crack initiation, the superimposed HCF-load causes whereas a accelerated crack propagation along occurred slip bands within the aluminium-mixcristal and zones of eutectical structure (Figure 7). At pure TMF-tests, crack-propagation only occurs along the eutectical structure.

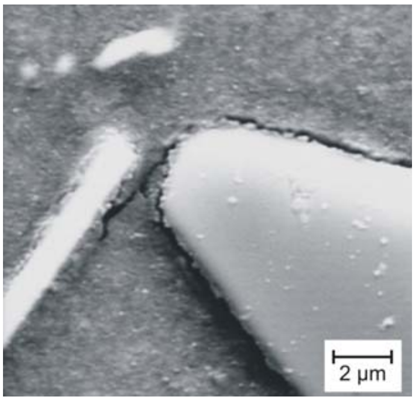

Figure 6: Separation of silicon particles within the aluminium-mixcristal

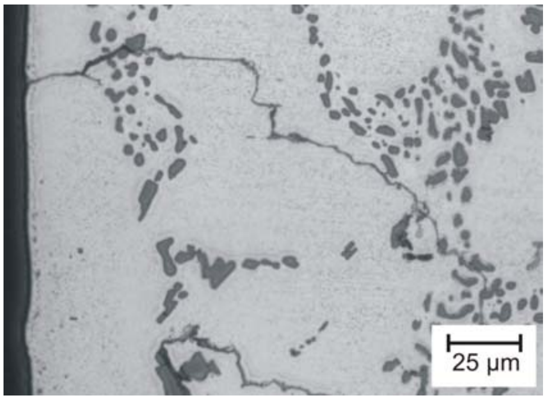

Figure 7: Crack-propagation at TMF/HCF-loading

4 ACKNOWLEDGEMENT

The authors gratefully acknowledge the financial support received from the Bundesministerium für Bildung und Forschung under the Project no. 03N3095.

5 REFERENCES

[1] Flaig B., Lang K.-H., Löhe D., Macherauch E.: Thermal-Mechanical Fatique of the Cast Aluminium Alloy GK-AlSi10Mg wa in: J. Bressers, L.Remy (eds.): Fatique under Thermal and Mechanical Loading, Kluwer Academic Publishers, 1996, S.361-370

[2] Beck T., Lang K.-H., Löhe D.: Thermal-Mechanical Fatigue Behaviour of Cast Aluminium Alloys for Cylinder Heads Reinforced with 15 Vol.-% Discontinous Al_2O_3 (Saffil) Fibers, *Mat. Sci. Eng.* A 319-321 (2002), S.662-666

[3] Sehitoglu H., Smith T.J., Maier H.J.: Thermo-mechanical Deformation of Al319 – T7B with Small Dendrite Arm Spacing, Thermo-mechanical Fatigue Behaviour of Materials, Third Volume, ASTM STP 1371, 2000