THERMAL-MECHANICAL FATIGUE BEHAVIOUR OF CAST ALUMINIUM ALLOYS

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ABSTRACT Thermal-mechanical fatigue (TMF) and isothermal fatigue (IF) tests under total strain control were performed at three cast aluminium alloys used for automotive applications, GK-AlSi10Mg and GK-AlSi12CuMgNi, both in the peak hardened state (T6) and GK-AlSi6Cu4 in the normalised state (O). Under thermal-mechanical fatigue loading with total strain constraint, a minimum temperature of $T_{min} = 50\ ^0C$ and a maximum temperature of $T_{max} = 250\ ^0C$, GK-AlSi10Mg and GK-AlSi12CuMgNi show cyclic softening which is essentially caused by overageing. Under the same loading conditions, GK-AlSi6Cu4 shows cyclic hardening during the first 100 cycles followed by slight cyclic softening until macroscopic crack initiation. A comparison of the corresponding Woehler curves for total strain amplitude and Coffin-Manson plots shows that TMF tests result in lower lifetimes than IF experiments for the whole temperature range investigated. Even an assessment of the TMF as well as the IF lifetimes using the Smith-Watson-Topper parameter shows that IF tests lead to a significant overestimation of the number of cycles to fracture compared with the results under TMF conditions.

Keywords: *Cast Aluminium Alloys, Thermal-Mechanical Fatigue, Cyclic Deformation Behaviour, Damage Parameter, Lifetime Estimation*

1. INTRODUCTION

Cast aluminium alloys are broadly used in car engines because of their low density, good heat conductivity, high specific strength, good wear resistance and castability. Components such as cylinder heads and pistons are subjected to very high thermal-mechanical fatigue (TMF) loadings during each start-stop cycle of an engine. For this reason, the lifetime of these engine parts often is determined by the thermal-mechanical fatigue resistance of the used materials. In many cases, data from isothermal fatigue (IF) tests are used for dimensioning construction parts made of cast aluminium alloys because results from TMF tests are not available. However, the lifetimes under TMF loading may be distinctly overestimated by the lifetime results of IF tests as it is shown in [1] for a cast nickel base superalloy. Therefore, tests with loadings as close as possible to the ones within the critical zones of pistons or cylinder heads under service conditions have to be performed. Simple thermal shock tests often show a large scatter of the revealed lifetime data and a quantitative evaluation of such tests, e.g. the derivation of the cyclic stress-strain or cyclic deformation behaviour, is very difficult [2].

Therefore, in the present work, TMF tests with temperatures approximate to the the ones occuring under service conditions were carried out with total strain constraint on three cast aluminium alloys used for pistons and cylinder heads of car engines. The lifetime- and cyclic deformation behaviour resulting from these tests is presented and discussed. For one of the materials investigated, the differences between the TMF and the IF behaviour are discussed. Results from standard IF tests with a frequency of 5 Hz are presented as well as results from IF tests at the maximum temperature and the same frequency as the respective TMF tests.

2. MATERIALS AND TESTING SPECIMENS

The tests were carried out at the cast aluminium alloys GK-AlSi10Mg and GK-AlSi12CuMgNi, both in the peak hardened state (T6) and at the alloy GK-AlSi6Cu4 in the normalised state (O). The chemical composition of the chill cast materials is given in Table 1, the heat treatment in Table 2. The microstructure of AlSi10Mg shown in Fig. 1 consists of primarily solidified α-Al phase and the globular eutectic consisting of β-Si and α-Al phase. GK-AlSi12CuMgNi shows a lamellar and GK-AlSi6Cu4 a more granular eutectic beside the primarily solidified α-Al phase. Additionally, GK-AlSi12CuMgNi contains nickel and copper rich phases.

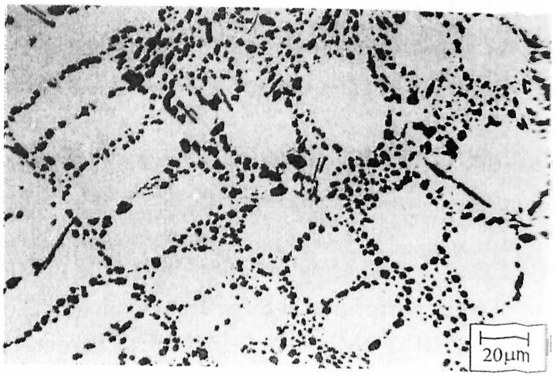

Fig. 1: Microstructure of the cast aluminium alloy AlSi10Mg

The β' (Mg_2Si) phase which is precipitated during hardening of GK-AlSi10Mg and GK-AlSi12CuMgNi is not visible in Fig. 1 because of their small size.

From the heat treated raw materials, solid cylindrical specimens were turned with a gauge length of 10 mm and a diameter of 7 mm in the gauge length [3].

Table 1: Chemical composition of the investigated materials [ma.-%]

	Si	Mg	Cu	Ni	Fe	Mn	Zn	Ti	Al
GK-AlSi10Mg	9,53	0,41	0,01	-	0,13	0,01	0,03	0,08	bal.
GK-AlSi12CuMgNi	11,20	1,01	1,15	1,03	0,36	0,27	0,05	0,01	bal.
GK-AlSi6Cu4	6,46	0,24	3,32	0,04	0,42	0,30	0,56	0,17	bal.

Table 2: Heat treatments

	solution annealing	quenching (water)	hardening
GK-AlSi10Mg	520°C / 5h	20°C	170°C / 5h
GK-AlSi12CuMgNi	500°C / 2h	80°C	210°C / 6h
GK-AlSi6Cu4	390°C / 3h	-	-

3. EXPERIMENTAL DETAILS

The thermal mechanical fatigue tests were performed on a 100 kN electromechanical testing machine with an inductive heating system. The specimens were cooled by thermal conduction to the water cooled grips and additionally by a controlled air jet to the surface of the specimen. A 100 kN servohydraulic testing machine with a resistance furnace was used for the isothermal fatigue tests.

TMF tests were carried out at all three materials investigated. The minimum temperature of the triangular shaped temperature-time cycles generally was T_{min}=50°C, the maximum cycle temperature was varied between T_{max}=200 °C and 350 °C. The ultimate number of cycles N_u was $2\cdot10^4$. Every cycle lasted 60s. The tests were started by heating the specimen to the mean temperature of the following cycles $T_m=(T_{max}+T_{min})/2$ without external force. After that, the total strain ε_t remained constant at the thermal strain value $\varepsilon^{th}(T_m)$ throughout the test. This corresponds to an ideally rigid clamping of the specimens ($\varepsilon_t=\varepsilon^{th}(T_m)$=const). From the measured stress-temperature loops, stress-total mechanical strain hystereses were derived using the transformation $\varepsilon_t^{me}(T)=\varepsilon_t-\varepsilon^{th}(T)$. $\varepsilon^{th}(T)$ was measured by dilatometry. From the stress-total mechanical strain hystereses, the stress amplitude and mean stress as well as the plastic strain amplitude were determined.

The IF tests were performed on the alloy GK-AlSi10Mg with triangular total strain-time signals. One set of tests was done at the temperatures T=20°C, 150°C, 250°C and 350°C with a frequency of 5Hz, a strain ratio $R_\varepsilon=-1$ and an ultimate number of cycles of $2\cdot10^6$. Additionally, a second set of IF experiments was carried out at T= T_{max} with the same mechanical strain amplitude and the same cycle time as the corresponding TMF tests. R_ε also was -1.

4. RESULTS AND DISCUSSION

4.1 Thermal-Mechanical Fatigue

Fig. 2 shows the maximum temperature T_{max} versus the number of cycles to fracture N_f at a constant minimum temperature T_{min}=50°C for the three cast aluminium alloys examined. In the range 200°C≤T_{max}≤300°C, the lifetimes of all three materials lie in one scatter band, whereas for T_{max}=350°C GK-AlSi10Mg shows a lower number of cycles to failure than the other cast aluminium alloys. At this maximum temperature, the specimens made of GK-AlSi10Mg do not fail by fracture but by mechanical instabilities leading to barrel shaped bulgings within the gauge length caused by massive plastic deformation while heating to maximum temperature. This different damage mechanism results in a smaller lifetime compared to the both other materials. The Woehler curves of the tested materials for total mechanical strain amplitude induced by TMF loading are shown in Fig. 3. The curves for GK-AlSi6Cu and GK-AlSi12CuMgNi are nearly identical whereas for GK-AlSi10Mg the curve is shifted to smaller lifetimes at all loadings. The differences of the calculated total mechanical strain amplitudes at $N_u=10^4$ which correspond to a maximum temperature T_{max}=200°C, are caused by the different thermal expansion coefficients of the materials investigated.

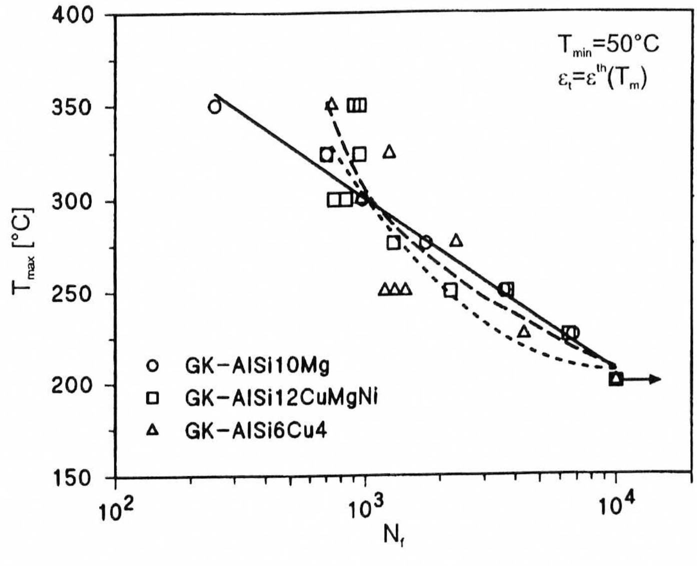

Fig.2: Temperature Woehler curves for TMF loading

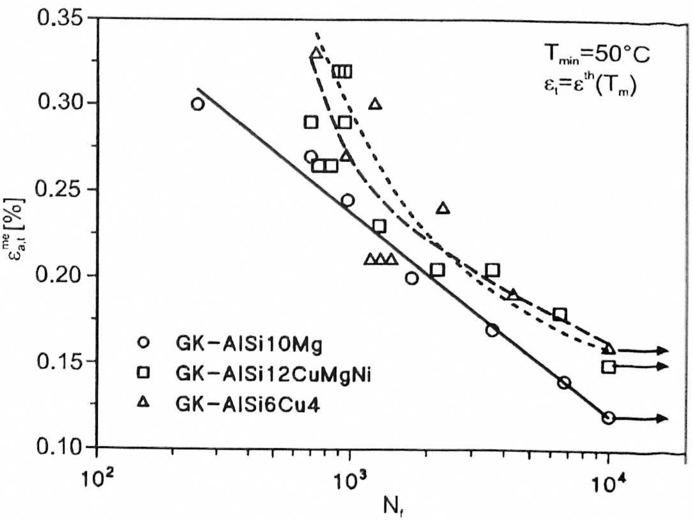

Fig. 3: Woehler curves for total mechanical strain amplitude

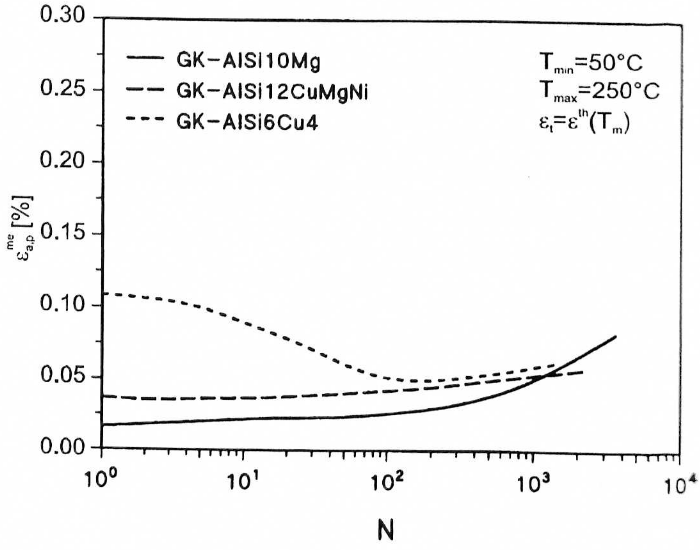

Fig.4: Cyclic deformation behaviour under TMF loading

An example for the cyclic deformation behaviour of the three cast aluminium alloys under thermal-mechanical fatigue loading is shown in Fig. 4, in which the plastic strain amplitude $\varepsilon_{a,p}^{me}$ is plotted versus the number of cycles for T_{min}=50°C and T_{max}=250°C. GK-AlSi10Mg and GK-AlSi12CuMgNi show increasing plastic strain amplitudes with growing numbers of cycles, which means cyclic softening during the whole experiments. This results from the transformation of the β'-phase precipitated during the T6 treatment to coarser, stable β-precipitations which are less effective obstacles to dislocation movement than the very fine dispersed β'-phase [3]. For GK-AlSi10Mg, stronger cyclic softening is observed than for GK-AlSi12CuMgNi, especially for N > 500, because the overageing processes explained above are more pronounced in GK-AlSi10Mg than in GK-AlSi12CuMgNi. The deformation behaviour of GK-AlSi6Cu under TMF loading is characterised by cyclic hardening up to N=200 followed by cyclic softening until fracture. The initial cyclic hardening is caused by an increase of the dislocation density and dislocation pileup processes. The subsequent cyclic softening is due to dislocation rearrangements caused by plastic deformations [3].

4.2 Comparison between Isothermal and Thermal-Mechanical Fatigue

Fig. 5 shows Woehler curves for total strain amplitude measured in isothermal fatigue experiments with a frequency of 5Hz and several temperatures between 20°C and 350°C for the material GK-AlSi10Mg. The diagram also includes the total mechanical strain Woehler curve resulting from TMF tests with T_{min} = 50°C and different maximum temperatures (see chapter 4.1). Regarding equal total strain amplitudes, TMF tests always lead to smaller lifetimes than isothermal experiments at any temperature investigated. Even isothermal fatigue tests at 350°C, which was the highest maximum temperature of the TMF-tests, result in markedly higher lifetimes than TMF experiments. The comparison of the corresponding Coffin-Manson curves in Fig. 6 shows that no isothermal reference temperature exists, which allows an accurate description of the material behaviour under TMF loading with the chosen minimum temperature of 50°C. A further possibility to compare the material behaviour under TMF and IF loading conditions is the application of the Smith-Watson-Topper damage parameter P_{SWT}, which is defined herein as

$$P_{SWT} = \sqrt{\varepsilon_{a,t} \cdot \sigma_{max} \cdot E} \qquad (1)$$

in which $\varepsilon_{a,t}$ is the total strain amplitude (for TMF the total mechanical strain amplitude), σ_{max} the induced maximum stress at $N_f/2$ and E the Young's modulus either at the test temperature (IF tests) or at the mean temperature (TMF tests). Fig. 7 shows P_{SWT} divided by the tensile strength R_m versus the number of cycles to fracture. For the IF tests, the R_m value at the test temperature and for the TMF tests R_m at mean temperature was used. Obviously, the results from IF and from TMF tests, respectively, can be described with two different straight lines in this kind of plot. But for equal P_{SWT}/R_m values, isothermal fatigue leads to at least 10 times higher numbers of cycles to fracture than thermal-mechanical fatigue.

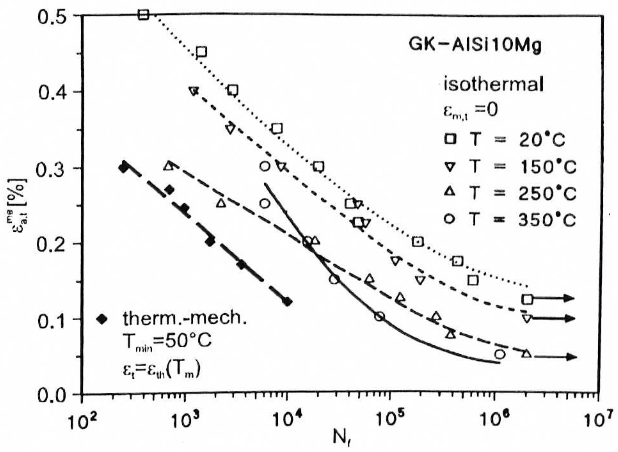

Fig. 5: Woehler curves for total strain under IF and TMF

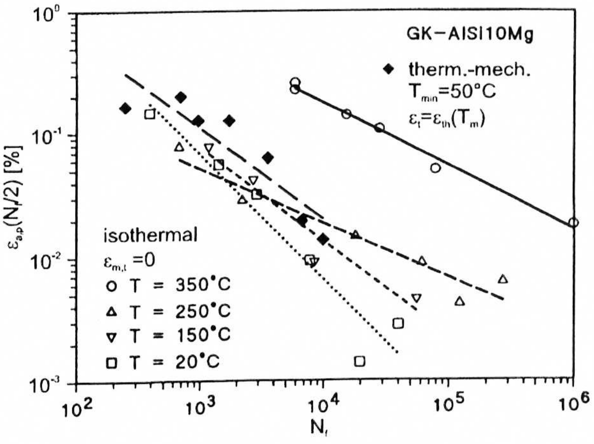

Fig. 6: Coffin-Manson plot for IF and TMF loading

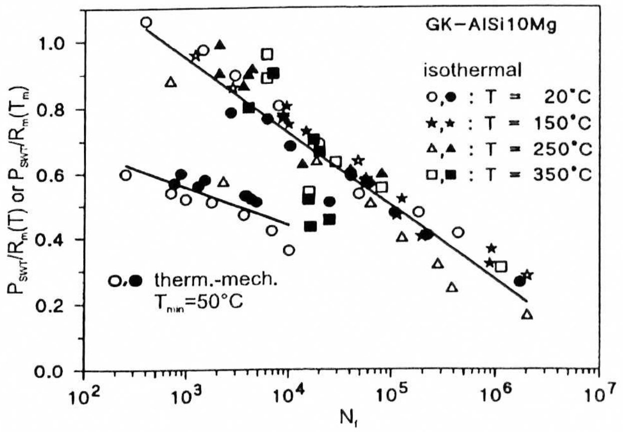

Fig. 7: P_{SWT} damage Parameter for IF and TMF loadings

The underestimation of the lifetimes under TMF loading by the IF experiments reported above might be caused by different cycle frequencies, because the TMF tests result in total mechanical strain rates of about $1\cdot10^{-4}\ s^{-1}$ whereas the total strain rate for the IF experiments is about $5\cdot10^{-2}\ s^{-1}$. To exclude this influence of frequency, some additional IF test were carried out at GK-AlSi10Mg with the same cycle time as at the TMF experiments. Moreover, the total mechanical strain amplitude was chosen to the value arising from TMF cycles with the same maximum temperatures as the IF testing temperatures. Fig. 8 shows the Woehler curves for total mechanical strain resulting from these IF tests compared to the TMF results for the same material. It can be seen, that even under these "worst case" isothermal fatigue conditions, IF tests lead to significant higher numbers of cyles to fracture than the corresponding TMF experiments. So it can be stated that the lifetime behaviour of the investigated cast aluminium alloy under thermal-mechanical cyclic loading cannot be described satisfying with results from isothermal tests.

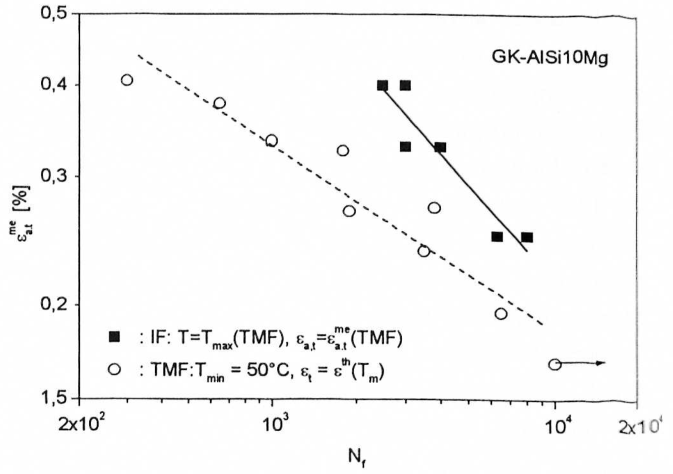

Fig. 8: Woehler curves for total strain amplitude from IF and TMF tests both with a cycle time of 60s

5. SUMMARY

An assessment of the thermal-mechanical fatigue resistance of the cast aluminium alloys investigated using data obtained from isothermal fatigue tests leads to a significant overestimation of the number of cycles to fracture. Therefore, a secure dimensioning of components loaded by thermal-mechanical fatigue is only possible using material data obtained from TMF-tests.

6. ACKNOWLEDGEMENT

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