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Lifetime of cast AlSi6Cu4 under superimposed thermal–mechanical fatigue and high-cycle fatigue loading

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Abstract

Out-of-phase thermal–mechanical fatigue (TMF) tests with superimposed high-cycle fatigue (HCF) loading were performed at the cylinder-head alloy AlSi6Cu4. For continuously superimposed HCF loading during TMF cycles with maximum temperatures of 250 and 300 °C a threshold of the amplitude of the superimposed HCF loading exists below which the number of TMF cycles to failure is not significantly affected. Above this threshold the TMF life shows a strong decrease with increasing HCF loading. This characteristic lifetime behaviour is also found in the case that HCF loading is only superimposed while tensile stresses are induced in the specimen during the TMF cycle. However, in the case that the HCF loading is superimposed only during the compressive phase of the TMF cycle, the number of TMF cycles to failure is not significantly affected.
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1. Introduction

Cast aluminium alloys used for cylinder heads, engine blocks and pistons of car engines undergo complex thermal and mechanical fatigue loadings [1,2]. On the one hand, the inhomogeneous and time-dependent temperature fields during start–stop processes result in thermally induced fatigue loadings with low frequency and, especially in the "hot" regions of the components, large plastic strain amplitudes. This "low frequency" part of the service loading can be simulated by thermal–mechanical fatigue (TMF) testing of uniaxially loaded specimens. In the recent decades, a remarkable amount of experimental TMF work has been carried out on this class of alloys [3–7].

On the other hand, the combustion pressure and oscillating masses result in a mechanical fatigue loading with distinctly higher frequencies and smaller strain amplitudes than the thermal fatigue cycles. Even a larger amount of materials data is available from isothermal high-cycle fatigue (HCF) testing on typical cast aluminium alloys for engine applications than from TMF loading [8–11].

However, only few studies on the lifetime behaviour of Al-alloys under low frequency TMF loadings superimposed with higher frequency mechanical HCF loadings are published up to now. TMF/HCF tests at a Ni-base wrought alloy showed that linear damage accumulation hypotheses are not applicable under such combined loadings [12]. TMF/HCF tests on cast Al–Si alloys resulted in a similar finding [13–15]. However, there is still a great lack of experimental data of TMF/HCF tests on cast aluminium alloys and the respective damage and failure mechanisms are up to now just qualitatively understood.

The present paper deals with the lifetime behaviour of a typical cast aluminium alloy used for cylinder heads under such TMF/HCF loadings. Special attention is paid to the influence of HCF cycles superimposed either in the tensile phase or in the compressive phase of the TMF cycle compared with the TMF life in the case that HCF loadings are superimposed during the complete TMF cycle.

2. Experimental details

2.1. Test material

TMF- and superimposed TMF/HCF-testing was performed at the cast cylinder-head alloy AlSi6Cu4. The material was solution annealed at 390 °C and afterwards air cooled to room temperature. The microstructure is characterized by dendritic α-Al crystals with a dendrite arm spacing of approximately 40 μm

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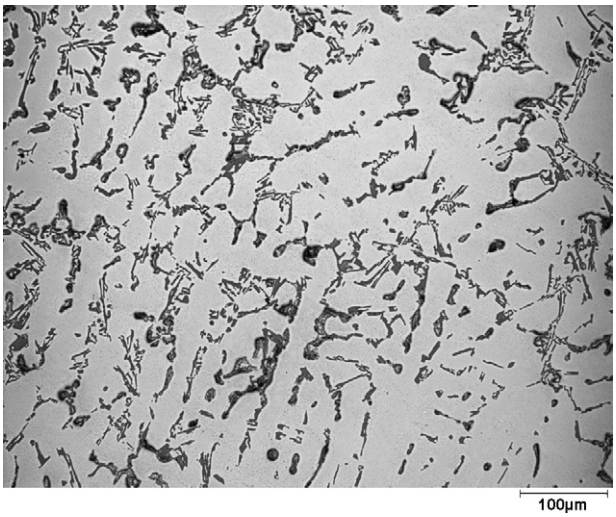

Fig. 1. Microstructure of AlSi6Cu4 in the as-received state.

and finely dispersed, round eutectic silicon (Fig. 1). Solid cylindrical specimens were used with a gauge section of 11 mm in length and 7 mm in diameter.

2.2. Test setup

The TMF and the superimposed TMF/HCF tests were performed on a servohydraulic fatigue testing machine with 100 kN maximum load. The computerized control unit allows to switch from force to strain control during a running test. For strain measurement, a water cooled capacitive high temperature extensometer with a gauge length of 15 mm was applied. Force was measured by the built in load cell of the testing machine. The specimen was heated by a 5 kW induction generator operating at a frequency of about 200 kHz. Cooling was mainly achieved by heat conduction into the water cooled grips. If necessary, additional forced cooling could be achieved by three nozzles blowing compressed air radially to the surface of the test piece. For temperature, closed loop control was achieved by a digital process controller. The setpoints for temperature and mechanical loading were generated by a PC based system which also performed the data acquisition with about 1000 measured values per cycle.

2.3. Test conditions

The TMF cycles had in all tests a minimum temperature of 50 °C and a heating and cooling rate of 10 K/s. The maximum temperatures T_{max} were 250 and 300 °C. Dwell times t_d at T_{max} of 0 s (triangular T–t cycle) and 180 s were applied. At the beginning of each test a dynamic thermal equilibrium in the test rig was achieved by five temperature cycles at zero stress. In the last of these cycles, the thermal strain εth was measured as a function of time and temperature. Afterwards, strain controlled out-of-phase TMF cycles were applied with complete constraint of the thermal strain (total strain ε_t = constant) resulting in a total mechanical strain ε_t^{me} (TMF) with the same amplitude as the thermal strain.

The superimposed HCF loading was also applied in total strain control and directly added to the ε_t-time path of the TMF cycle. The HCF cycles had a frequency of $f_{HCF} = 5$ Hz. The amplitude $\varepsilon_{a,t}^{me}$ (HCF) was varied between 0.02% and 0.08% and was therefore significantly lower than the mechanical strain amplitudes from TMF loading $\varepsilon_{a,t}^{me}$ (TMF) which lies between 0.2% and 0.4%. In most of the TMF/HCF tests the HCF loading was applied during the complete TMF cycle. A typical resulting hysteresis loop of nominal stress σ_n versus total mechanical strain $\varepsilon_t^{me} = \varepsilon_t^{me}$ (TMF) + ε_t^{me} (HCF) is given in Fig. 2a. In further test series, superimposed HCF loading was applied only during 5 s in the tensile phase of the TMF cycle at $T \approx T_{min}$ (Fig. 2b) or in the compressive phase at $T \approx T_{max}$ (Fig. 2c). Additionally, some TMF tests with $t_d = 180$ s and HCF cycles superimposed during the complete dwell time at T_{max} were performed (Fig. 2d). The tests were stopped at an ultimate number of TMF cycles of 10^4 or when the specimen failed by fracture.

3. Results

The influence of superimposed HCF-loadings with $\varepsilon_{a,t}^{me}$ (HCF) = 0.02% up to 0.08% on the TMF-life for a maximum temperature of 250 °C is given in Fig. 3. Results of tests without dwell time at T_{max} are represented by squares, those with a dwell time of 180 s by triangles. Open symbols indicate TMF tests without superimposed HCF loading, full symbols TMF tests with HCF loading superimposed during the complete TMF cycle. TMF tests with HCF cycles superimposed during 5 s in the tensile phase of the TMF cycle (Fig. 2b) are represented by symbols with an (+), tests with HCF loading only in the compressive phase of the TMF cycle (Fig. 2c) by symbols with a (X). TMF tests with superimposed HCF loading during 180 s dwell at T_{max} are marked by a (−). TMF tests without a dwell time result in numbers of cycles to failure N_f of approximately 6000 (□), for $t_d = 180$ s N_f is about 4500 cycles (△). In both cases a threshold value of $\varepsilon_{a,t}^{me}$ (HCF) = 0.02% can be noticed, below which the TMF life is not affected significantly by the superimposed HCF loading. Higher HCF-amplitudes superimposed during the complete TMF cycle lead to a significant decrease of TMF life. This lifetime reduction is more pronounced for TMF/HCF tests with dwell time that results in a larger number of superimposed HCF cycles per TMF cycle than in the case of $t_d = 0$ s. In the case of TMF cycles without dwell, superimposed HCF loading during 5 s in the tensile phase of the TMF cycle results in nearly the same TMF life as superimposed HCF loading during the complete TMF cycle, whereas HCF loading superimposed during 5 s in the compression phase of TMF cycles does not affect TMF life. On the other hand, superimposed HCF cycles during a dwell time of 180 s as well as with superimposed HCF during 5 s in the tensile phase of the TMF cycle with $t_d = 180$ s lead to TMF lifetimes between the respective values of pure TMF loading and with HCF loading superimposed during the complete TMF cycle.

Fig. 4 shows the corresponding results for a maximum temperature of the TMF cycles of 300 °C. The meaning of the used symbols is the same as in Fig. 3. The lifetime for pure TMF loading is about 2000 cycles for $t_d = 180$ s and 3000 for tests without

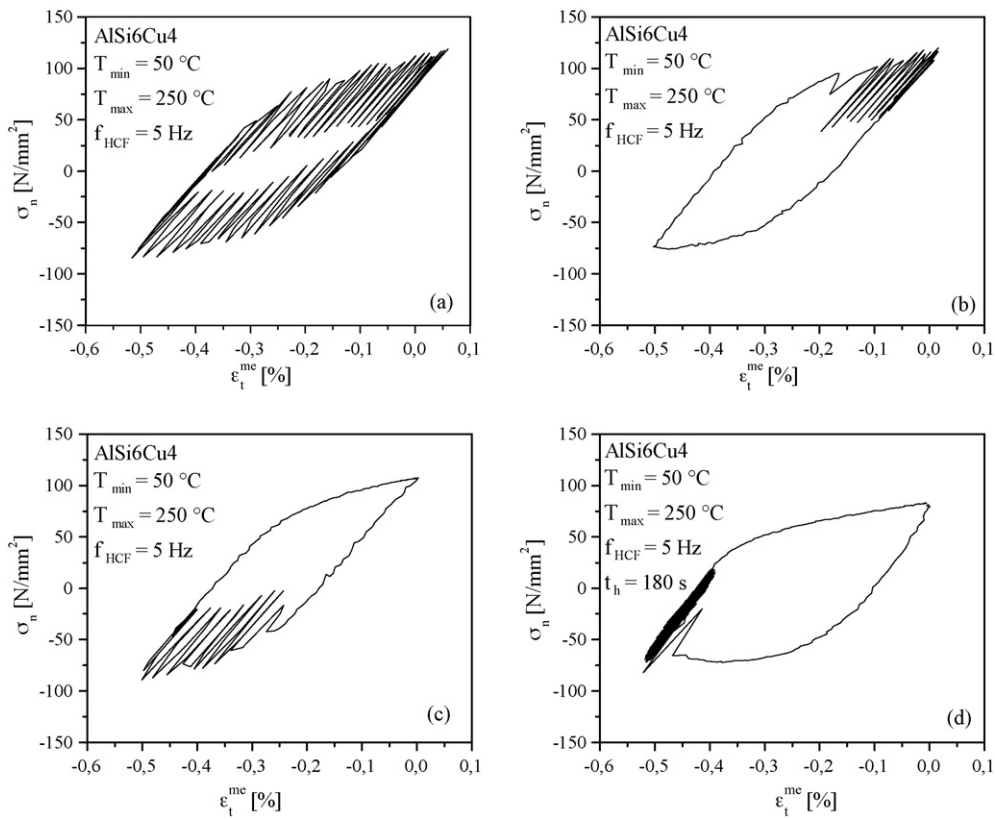

Fig. 2. σ_n–ε_t^{me} hystereses for TMF tests with superimposed HCF during the complete cycle (a), superimposed HCF only in the tensile phase (b), only in the compressive phase (c) and during the dwell time at T_{max} of the TMF cycle.

dwell. Again, HCF cycles superimposed during the complete TMF cycle result in a strong decrease of TMF life as soon as $\varepsilon_{a,t}^{me}$ (HCF) exceeds a threshold value of 0.02%. As also observed for $T_{max} = 250\,°C$, the lifetime of TMF tests without dwell is not affected by superimposed HCF loading only in the compressive phase of the TMF cycle, whereas 5 s of superimposed HCF in the tensile phase of the cycle results in nearly the same lifetime reduction as HCF loading superimposed during the complete TMF cycle. For $t_d = 180$ s the TMF lives for HCF loading superimposed during the complete dwell time and only during 5 s in the tensile phase of the TMF cycle both lie between the results of TMF tests without HCF and with HCF loading superimposed during the whole TMF cycle.

4. Discussion

The lifetime and damage behaviour of cast Al cylinder-head alloys under TMF and superimposed TMF/HCF loadings was presented and extensively discussed in a PhD thesis [14] and in a previous paper [15]. From this research the following indications were obtained about the threshold of $\varepsilon_{a,t}^{me}$ (HCF) below of which TMF life is not affected significantly and the strong decrease of

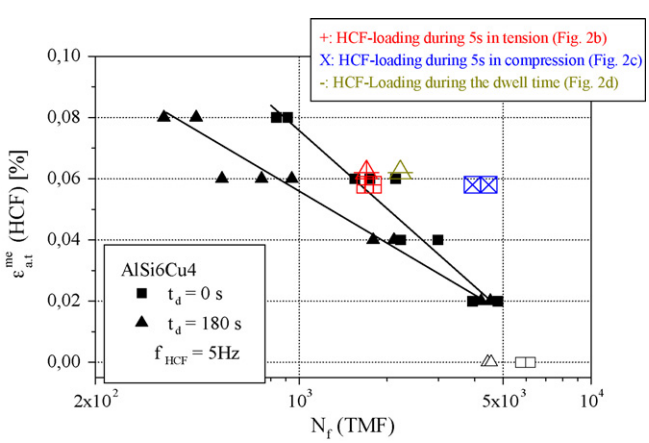

Fig. 3. Lifetime behaviour at TMF/HCF loading with $T_{max} = 250\,°C$, $\varepsilon_{a,t}^{me}$ (TMF) = 0.225%.

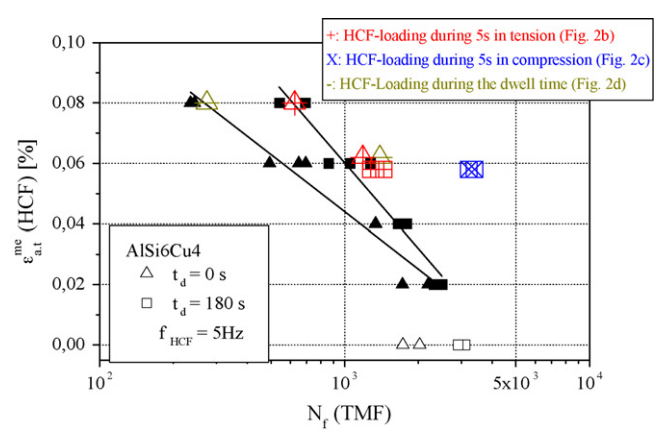

Fig. 4. Lifetime behaviour at TMF/HCF loading with $T_{max} = 300\,°C$, $\varepsilon_{a,t}^{me}$ (TMF) = 0.275%.

TMF life as soon as this threshold is exceeded:

- The cyclic deformation behaviour and especially the amount of plastic deformation before first cracks are formed are mainly determined by the TMF cycle, whereas the HCF loading results, due to its small amplitude and high frequency, in nearly elastic deformation.
- Consequently, the formation of first cracks is mainly caused by the TMF loading. The plastic strain amplitude and the peak stress induced by the TMF cycle determine the number of cycles to crack initiation.
- As soon as a threshold of $\varepsilon_{a,t}^{me}$ (HCF) $\approx 0.02\%$ is exceeded, the crack propagation is strongly accelerated by the superimposed HCF loading. It should be noted that even small $\varepsilon_{a,t}^{me}$ (HCF), which still lie below the fatigue limit at isothermal loading, obviously result in a strong increase of the crack propagation rate.

In TMF tests without dwell time at T_{max}, 5 s of superimposed HCF loading in the tensile phase of the TMF cycle (Fig. 2b) have the same influence on TMF life as continuously superimposed HCF cycles (Fig. 2a), whereas HCF cycles superimposed while the TMF cycle induces negative stresses (Fig. 2c) do not affect the number of TMF cycles to failure significantly. This supports the assumption that the reduction of TMF life due to superimposed HCF loadings is mainly caused by an accelerated propagation of cracks that are initiated by TMF loading in a quite early stage of the tests. Fatigue crack propagation in isothermal HCF loading is also strongly affected by mean stresses: In the absence of residual stresses, compressive mean stresses that result in peak stresses below zero result in no or extremely slow crack propagation, whereas increasing tensile mean stresses effect strongly increasing crack propagation rates [16]. As becomes obvious in Fig. 2c, in the case of five seconds of superimposed HCF loading in the compressive phase of the TMF cycle, the maximum stresses resulting from the superimposed HCF remain below zero. Therefore, the superimposed loading neither influences the crack propagation rate nor the TMF lifetime. On the other hand, high tensile mean stresses result in a strongly accelerated fatigue crack propagation. This situation occurs when HCF is superimposed during the tensile phase of the TMF cycle. The fact that nearly identical TMF lives are measured for HCF loading superimposed during the complete TMF cycle with $t_d = 0$ s and during 5 s in the tensile phase of the same TMF cycle gives evidence that lifetime behaviour under TMF/HCF loading without dwell is strongly affected by the HCF cycles with tensile mean stresses.

On the other hand, in the case of TMF with 180 s dwell time at T_{max}, the TMF lives of both, tests with HCF superimposed during 5 s in the tensile phase and during the complete dwell time, lie between the lifetimes for TMF with HCF loading in the complete cycle and that under pure TMF loading. A closer look at Fig. 2d gives evidence that due to the relaxation of compressive stresses in the dwell time the maximum values of the stresses induced by the superimposed HCF loading lie distinctly above zero. Consequently, these HCF cycles contribute to fatigue crack propagation and shorten TMF life. As expected, TMF life is also reduced in the case of superimposed HCF loading only during five seconds in the tensile phase of the TMF cycle. In the case of TMF tests with HCF loading superimposed during the complete cycle, both effects are adding to each other and lifetime is further reduced.

5. Conclusions

To analyze the synergy of damage caused by superimposed low frequency thermal–mechanical and higher frequency mechanical loading and to get quantitative fatigue life data under such loading conditions, superimposed out-of-phase thermal–mechanical fatigue (TMF)/high-cycle fatigue (HCF) tests at the cylinder-head alloy AlSi6Cu4 were conducted in total strain control. Maximum temperatures of $T_{max} = 250$ and 300 °C as well as dwell times at T_{max} of $t_d = 0$ and 180 s were applied. The superimposed HCF loading had a frequency of 5 Hz and mechanical strain amplitudes between $\varepsilon_{a,t}^{me}$ (HCF) = 0.02% and 0.08%.

Up to a threshold of $\varepsilon_{a,t}^{me}$ (HCF) = 0.02% the superimposed HCF loading does not reduce TMF lifetime significantly. However, at $\varepsilon_{a,t}^{me}$ (HCF) > 0.02% a decrease of TMF life is caused by superimposed HCF which is the more pronounced the higher the HCF amplitude and the dwell time at T_{max} are. HCF loadings above this threshold which result in positive peak stresses generally reduce TMF life. If HCF cycles are superimposed in compression and the maximum stresses induced by the superimposed loading do not exceed zero, TMF life is not affected.

In the case of a cylinder head, thermally induced tensile stresses mainly occur as the engine cools down after service where no superimposed HCF loading due to the combustion pressure is effective. On the other hand, superimposed HCF loadings generally occur during the start and service of an engine where compressive stresses are induced by thermal loading which suppress the lifetime reduction by superimposed HCF. However, if these compressive stresses at least partly relax, superimposed HCF loading can induce tensile maximum stresses which may lead to a decease of service life of the component.

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