THE INFLUENCE OF PRE-AGING, TEMPERATURE, MEAN AND LOCAL STRAIN ON LOW CYCLE AND THERMO-MECHANICAL FATIGUE

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ABSTRACT

Cyclic loading of metallic engineering components at constant elevated or fluctuating temperature causes a complex evolution of damage which can hardly be described in a unique and straightforward manner. The aim of this study is to separate the particular phenomena to understand them in detail before superimpose them. At specific low cycle fatigue (LCF) and out-of-phase thermo-mechanical fatigue (OP-TMF) test series at the aluminium wrought alloy AlCuBiPb (2011) the influence of pre-aging, temperature, mean strain, local strain and dwell time are investigated by means of the deformation and lifetime behaviour. When heat treated aluminium alloys are exposed to constant elevated or fluctuating higher temperatures in their service life, they show a temperature- and time-dependent ageing behaviour which can much decrease the mechanical properties. A constant elevated temperature at LCF as well as dwell time effects at the maximum temperature at TMF show a lifetime decreasing effect over the whole lifetime. Pre-aged specimens show markedly lower stress parts and higher plastic strain parts. The pulsating tests show compared to the alternating ones only a short lifetime decreasing effect predominantly at higher strain levels. At out-of-phase TMF the total mechanical strain in the case of rigid clamped specimens is the sum of a thermal strain part that is to be compensated and an additional local strain part. The value of the local strain depends on time-independent loading parameters as well as on time-dependent hardening and softening effects and is therefore varying over the lifetime.

1 INTRODUCTION

The influence factors on low cycle fatigue are investigated by the means of strain-controlled LCF tests, the influence factors on thermo-mechanical fatigue are investigated by the means of temperature-controlled TMF tests with rigid clamped specimens. The particular influence factors are divided up and separated in LCF and TMF investigations. In addition to the tests, metallographic light optical and scanning electron microscope investigations are presented.

2 MATERIAL AND EXPERIMENTAL PROCEDURE

The material used for this investigation is the aluminium wrought alloy AlCuBiPb (2011), with weight per cents of Cu 3.6, Fe 0.35, Pb 0.97, Bi 0.02, Si 0.17, Zn 0.05, Mn 0.63 and Mg 0,89. Because heat treated, this alloy rapidly looses its out-standing properties at room temperature, when exposed to elevated temperatures.

The total strain-controlled LCF tests are accomplished with number of cycles to failure from 10^0 to 10^6 to characterise the transition to the mono-cyclic region and to the stress-characterising HCF region. Investigated influence factors are elevated temperature, pre-aging and mean strain.

The specimens in the temperature-controlled TMF tests are clamped in the manner that no total mechanical strain within the unclamped specimen length is possible (out-of-phase TMF). Because of the special geometry of the planetoid induction coil, the temperature is constant over a wide range. It is measured in axial and radial symmetric position by a sheath-thermocouple that is situated directly in the parallel testing cross section of the hollow drilled specimen. The local strain part is measured with a ceramic rod extensometer in axial symmetric position also directly in the parallel testing cross section (Riedler [1, 2]). The TMF test matrix is spanned by the maximum temperature T_{max} and the dwell time at the maximum temperature t_{Dmax} with further influences of pre-aging, local strain and mean strain. The TMF tests are accomplished with a minimum temperature of T_{min}=40 °C and varying maximum temperatures from T_{max}=200 °C up to 300 °C and number of cycles to failure from about 10^2 to 10^4. The FE-analysis (Minichmayr [3]) of the effects in the specimens during TMF-testing with nonlinear kinematic material models is a good match for the measured local strains that results from the following two effects: On the one hand, the stresses in the outer region of the specimen are much smaller compared to the stresses in the testing section because of the specimen's waisted geometry. In addition the lower temperatures in this outer region because of an inescapable temperature distribution (cooling condition and induction coil geometry) lead to higher yield stresses. On the other hand the thermal strains are reduced in the outer region. Due to the first effect the plastic deformation is concentrated in the parallel testing cross section of the specimen; the second effect decreases the local strains. The total mechanical strain in the case of the rigid clamped specimen at out-of-phase TMF is the sum of the thermal strain part that is to be compensated and the additional local strain part. If describing the strain parts in the manner of amplitude values the mean strain part in the case of applied constant mean strains does not affect the total mechanical strain amplitude

$$\varepsilon_{a,t}^{mech} = \varepsilon_{a,t}^{th} + \varepsilon_{a,t}^{loc} \,. \tag{1}$$

To describe the total mechanical strain the factor K_{TM} is defined as the ratio of the mechanical strain and the thermal strain part (Minichmayr [3]), that can be described in amplitude values as

$$K_{TM} = \frac{\varepsilon_{a,t}^{mech}}{\varepsilon_{a,t}^{th}} = 1 + \frac{\varepsilon_{a,t}^{loc}}{\varepsilon_{a,t}^{th}} \,. \tag{2}$$

Although the temperature amplitude and the mean strain are constant during the test, the total mechanical strain amplitude is varying, because material hardening and softening affects the local strain. Because the LCF tests are executed in closed loop total mechanical strain control on a servo-hydraulic testing system, the mechanical strain is there equitable to the local strain and can therefore also be labelled as total strain to simplify matters.

For the presentation of the LCF and TMF results the combined model of Manson-Coffin (Manson [4], Coffin [5]) and Basquin ([Basquin [6]) is used to describe the lifetime behaviour. The total mechanical strain is the sum of an elastic and a plastic strain part dependent on the number of cycles to failure

$$\varepsilon_{a,t}^{mech} = \varepsilon_{a,e}^{mech} + \varepsilon_{a,p}^{mech} = (\frac{\sigma'_f}{E}) \cdot N_f^{\;b} + \varepsilon'_f \cdot N_f^{\;c} \,. \tag{3}$$

The model of Ramberg-Osgood (Ramberg [7]) represents a relation between stress and strain amplitude in fully reversed fatigue loading tests that also consists of an elastic and a plastic part

$$\varepsilon_{a,t}^{mech} = \varepsilon_{a,e}^{mech} + \varepsilon_{a,p}^{mech} = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{\frac{1}{n'}} \,. \tag{4}$$

3 INFLUENCE OF PRE-AGING

When heat treated aluminium alloys are exposed to elevated or fluctuating higher temperatures in their service life, they show a temperature- and time-dependent ageing behaviour which can much decrease the mechanical properties. To investigate these effects on low cycle and thermo-mechanical fatigue, LCF test series at room and higher temperatures, as well as LCF and TMF test series for pre-aged conditions were conducted. Moreover TMF test series with different dwell times at the maximum temperatures were conducted to additionally investigate creep effects.

The first investigation is the separated effect of pre-aging at an elevated constant temperature on the deformation and lifetime behaviour by the means of mono-cyclic and alternating LCF (strain ratio = -1) and OP-TMF (temperature ratio = -1) tests. Figure 1 shows the hysteresis loops for two different total strain levels for non pre-aged and pre-aged specimens at 250 °C for 500 h. At the same LCF strain-level the pre-aged specimens show stress values that are about the half compared to non pre-aged specimens. Figure 2 shows the influence of pre-aging on the deformation behaviour by means of mono-cyclic tensile tests and LCF tests. At the non pre-aged specimens a high stress hardening tendency can be seen compared to the tensile test. Pre-aging at 250 °C for 500 h leads to a striking smaller lifetime in the lower strained LCF region, as Figure 3 shows. The deformation behaviour of pre-aged specimens in the manner of stress-cycle or plastic strain-cycle plots shows a nearly straight line without distinctive hardening or softening parts, but a markedly higher plastic strain part, see Figure 5.

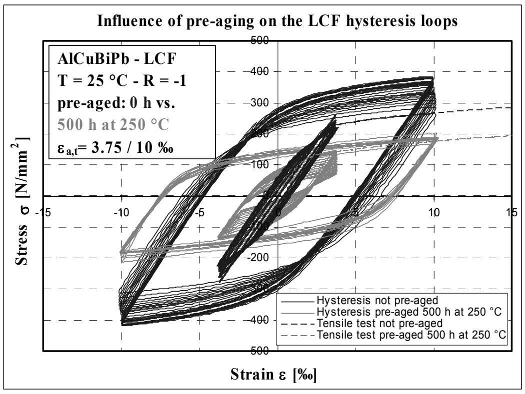

Figure 1: The influence of pre-aging on the LCF hysteresis loops

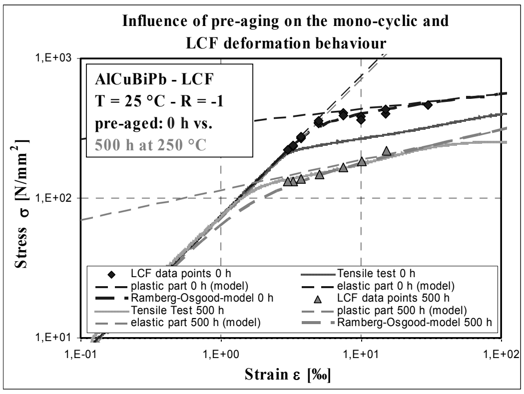

Figure 2: The influence of pre-aging on the LCF deformation behaviour

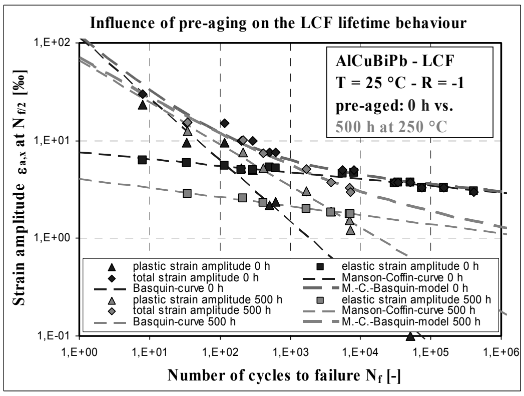

Figure 3: The influence of pre-aging on the LCF lifetime behaviour

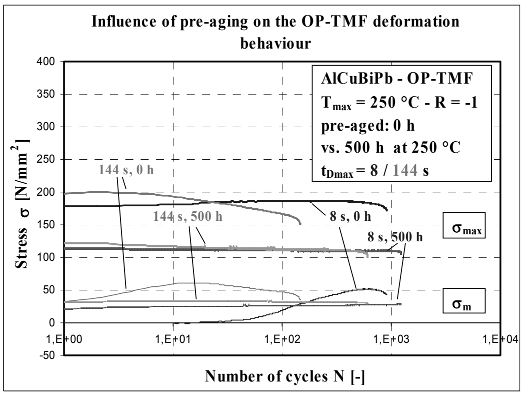

Figure 4: The influence of pre-aging on the TMF cyclic deformation behaviour

At the same TMF temperature-level pre-aged specimens at 250 °C for 500 h show the analogous deformation behaviour tendency as obtained at the LCF results, namely a decrease of about 50 per cent compared to non pre-aged specimens, see Figure 4. The influence of the dwell time decreases with increasing time and temperature of pre-aging. The differences in lifetime for the dwell time of 8 s and 144 s decreases from a factor more than 6 to a factor of 2, when the specimens are pre-aged for 500 h at 250 °C before tested. After extensive pre-aging the influences of dwell times completely disappear in face of the cyclic deformation and the lifetime behaviour.

3 INFLUENCE OF TEMPERATURE

A constant elevated temperature influences firstly the mono-cyclic material behaviour and secondly has a time-dependent effect because of hardening vs. softening effects during service life. In this section the time-dependent influence of a constant elevated temperature on LCF as well as the effect of the maximum temperature and the dwell time at the maximum temperature on TMF is investigated by means of non pre-aged specimens.

Because of AlCuBiPb being heat treated and with an ultimate strain of 20 per cent very ductile at room temperature, the material has its best LCF lifetime characteristics at room temperature. A constant elevated temperature of 200 °C leads to a higher damage of the material with differences in the lifetime in the order of magnitude of one decade compared to the room temperature results. Figure 5 shows the summarised presentation of the influences of pre-aging, constant elevated temperature and applied mean strain on the LCF deformation behaviour by means of the plastic strain amplitude part and Figure 6 by means of the strain-life curves. At a constant temperature of 200 °C the stress softening phase starts after a few cycles, what can also be seen in an increase of the plastic strain part in Figure 5.

The typical start-stop-operation of metallic engineering components as well as the alternating fired and non-fired operation causes dwell times at elevated temperatures with its harmful lifetime-decreasing effect. To study this effect out-of-phase TMF tests with four different dwell times at the particular maximum temperatures were conducted. At constant dwell time, an increase of the maximum temperature changes the pre-dominantly cyclic stress hardening behaviour to a pre-dominantly cyclic stress softening behaviour. On the other hand, at constant maximum temperature, an increase of the dwell time also changes the predominantly cyclic stress hardening behaviour to a pre-dominantly cyclic stress softening behaviour. Dependent on the maximum temperature, the influence of the dwell time causes differences in the lifetime in the order of magnitude of one decade. The analysis of the strain-life curves for the different dwell times shows regularities that provide an opportunity of a lifetime prediction depending of the dwell time (Riedler [2, 8, 9]).

4 INFLUENCE OF MEAN STRAIN

Impressed mean strains in the manner of pulsating LCF tests (strain ratio = 0) show a visible decrease in lifetime for higher strain levels and only a slight lifetime decreasing effect at lower strain levels, see Figure 6. At latest from the half of the number of cycles to failure $N_{f/2}$ on, the cyclic stress deformation curves follow a common progression. Some slight lifetime-decreasing effects ascertainable at pulsating executed test series mostly result from the first few cycles, where the higher tensile stresses and plastic strains (see Figure 5) cause higher damage rates.

The comparison of alternating and pulsating (temperature ratio = -1 vs. 0) executed TMF test series shows the same tendencies as at the LCF results. At latest from $N_{f/2}$ on, the cyclic stress deformation curves follow a common progression and only some slight lifetime-decreasing effects are ascertainable at pulsating executed test series.

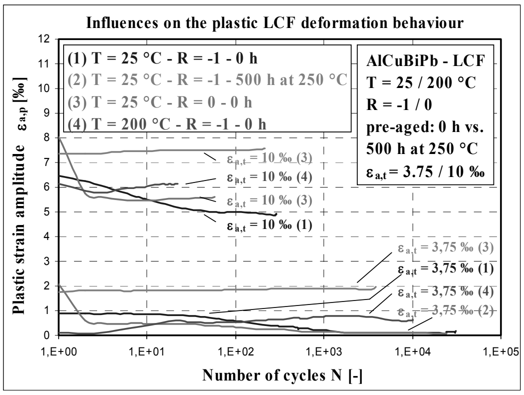

Figure 5: The influence of pre-aging, elevated temperature and mean strain on the LCF deformation behaviour

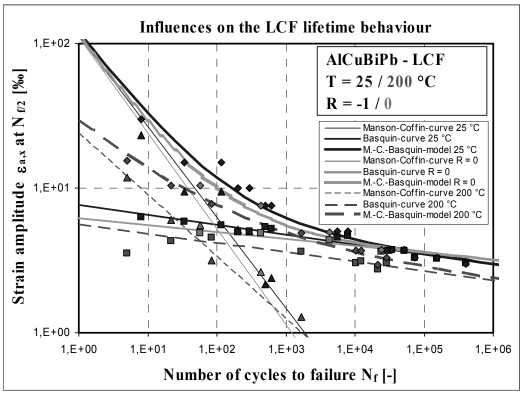

Figure 6: The influence of elevated temperature and mean strain on the LCF lifetime behaviour

5 INFLUENCE OF LOCAL STRAIN

As described before, at out-of-phase TMF tests with rigid clamped specimens there is an additional local strain part. The value depends on time-independent loading parameters as well as on time-dependent hardening and softening effects and is therefore varying over the lifetime. Figure 7 shows the dependency of the maximum temperature on the progression of the particular local strain parts. At a maximum temperature of 225 °C, the local strain amplitude is low over the whole lifetime with a continuous increase of a negative mean value. At 275 °C the local strain amplitude is more than the double of the thermal strain amplitude. Figure 8 compares the hysteresis loops from the thermal strain and the total strain for selected load cycles until $N_{f/2}$. The progression of the particular local strain parts (amplitude, maximum, mean and minimum) can also be seen in the appearance of the total strain hysteresis loops. The increase of a negative mean part of the total strain and a positive mean stress gives an idea of the plastification effects that have to take place in the testing cross section, which can also be seen at the fractured specimen in Figure 8.

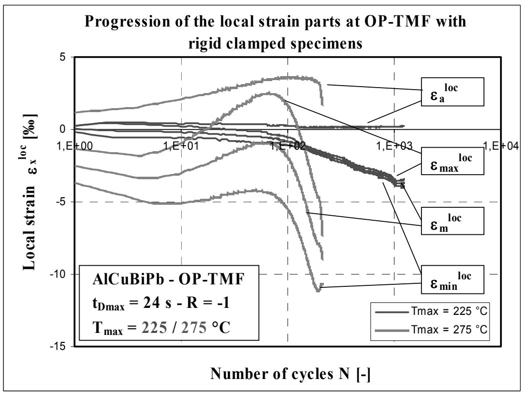

Figure 7: The progression of local strains at OP-TMF

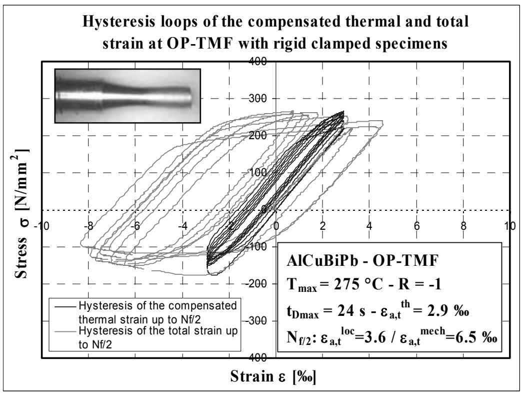

Figure 8: Hysteresis loops of the thermal and total strain at OP-TMF

6 METALLOGRAPHIC INVESTIGATIONS

Whereas etched as well as un-etched metallographic micrograph analysis of LCF and TMF strained specimens do not show any visible difference (Riedler [2]), the appearance of the fractured surface show markedly differences by means of light optical microscope and scanning electron microscope (SEM) analysis. Whereas both LCF and TMF fractured surfaces show a typically ductile view, the brittle, oxidised regions can mainly be obtained at TMF specimens, see Figure 9. The SEM picture of the whole area of a lower LCF strained specimen shows the typical oscillating fracture behaviour.

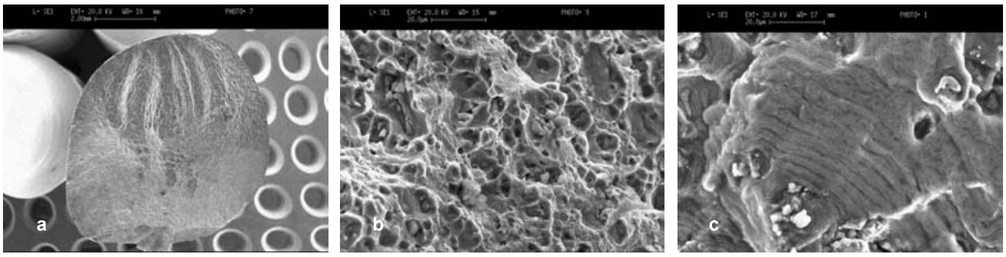

Figure 9: SEM-investigations: a) LCF strained fractured surface, b) ductile regions in the remaining fracture of LCF and TMF, c) brittle, oxidised regions mainly at TMF

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