EVALUATION OF CREEP BEHAVIOUR AND FATIGUE LIFE UNDER TMF-LOADING FOR ALLOY AlCuBiPb

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ABSTRACT

Two different principles of TMF-testing were investigated for the wrought aluminium alloy AlCuBiPb (2011). On the one hand the specimens are clamped in a stiff load frame in Out-of-Phase (OP) TMF loading. The local strain is measured within the parallel cross section of the specimen. On the other hand OP-TMF tests are conducted using strain control on a servo-hydraulic TMF testing system, which guarantees a rigid restraint condition within the parallel section of the specimen.

Because creep effects have to be considered in thermo-mechanical loaded components to take into account stress relaxation phenomena and creep damage, creep tests were carried out for the wrought aluminium alloy between 150°C and 300°C for a stress range from 90 to 250MPa. Multiple step creep tests were conducted to find an appropriate parameter for modeling the creep behavior under variable amplitude loading. In addition the microstructure and fracture surfaces were investigated in more detail using optical and scanning electron microscopy.

1 INTRODUCTION

The TMF-test of a clamped specimen under out-of-phase TMF loading without closed loop strain control gives an idea of the complex phenomena in TMF loaded components. The material behaviour is dependent on time, temperature, strain rate and accumulated plastic strain. Therefore the mechanical strain amplitude is not constant during service life, although the temperature amplitude is constant. When considering the local strains the results can be compared to tests from servo-hydraulic TMF-test-rigs.

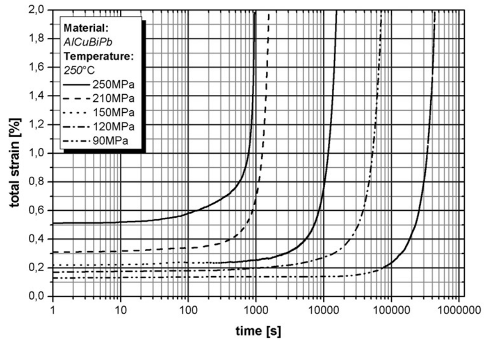
Creep tests and multiple step creep tests are carried out to take into account stress relaxation phenomena in the calculation of complex TMF-loaded components.

2 EXPERIMENTAL SETUP FOR CREEP TESTS

A test frame for creep tests is used. The load is applied using different weights and a lever with a variable ratio of 1:10 to 1:20. The temperature resistant extensometer, which is used for measuring the creep strain directly within the parallel testing section of the specimen, is located directly in the heat chamber. Creep test are conducted for a temperature range of 150°C to 300°C. The load level depends on the temperature and varies between 90MPa and 250MPa. In the multiple step tests the load was increased, when exceeding the point with minimum creep strain rate.

3 RESULTS OF CREEP TESTS

The measured creep curves exhibit a relatively short primary region directly followed by an extended tertiary stage. Secondary creep was not observed, see Figure 1. Due to ageing effects the decreasing strain rate of the primary creep stage directly merges into the stage of tertiary creep with material softening and therefore increasing creep strain rates. Figure 2 shows, that the minimum of the creep strain rate is always found between 0.1 and 0.2*t_f (t_f = time to fracture). The experiment at 250 MPa shows a different behaviour. This could be a result of the large pre-strain.



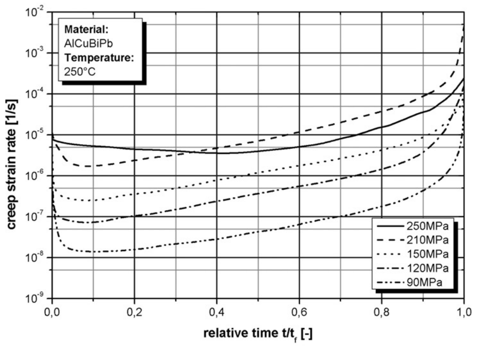


Figure 1: Creep curves at 250°C

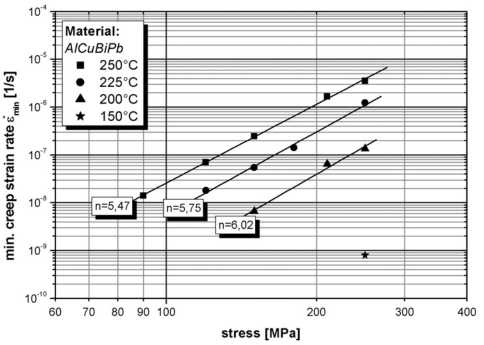
Figure 2: Creep strain rates at 250°C

The dependence of the minimum creep strain rate on the applied stress level and temperature can be described by eqn (1), where n is the Norton exponent and Q is the activation energy for the dominating creep process:

$$\varepsilon_{\min} = A \cdot \sigma^{n} \cdot e^{-\frac{Q}{R \cdot T}} \tag{1}$$

The test data show a strong dependence of the minimum creep strain rates on the stress level. The Norton exponents are about 5 – 7 (see Figure 3), which is rather high in the range of dislocation creep (Frost [1]). For very high stress levels the exponents become greater than 20, which is typical for the transition from creep to plastic deformation.

A value of 142 to 150kJ/mol was found for the activation energy depending on the stress level, as shown in Figure 4. Compared to 142kJ/mol (Gandhi [2]) for self-diffusion of pure aluminium, the calculated values seem to be very reasonable.



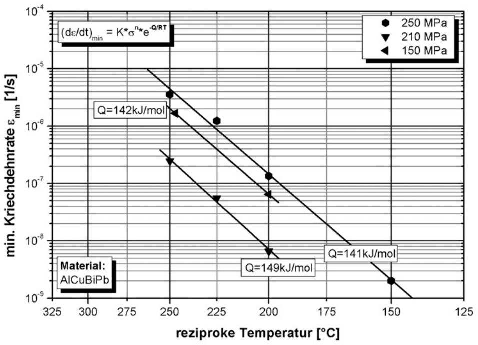


Figure 3: Min. creep strain rate vs. stress level

Figure 4: Determination of activation energies

Multiple step tests show, that neither strain or time, nor the simple parameter t/t_f are suitable to describe the creep behaviour in multiple step tests. Therefore different tests with varying pre-exposure-times at test-temperature were conducted. The pre-ageing time was chosen according to the total time in the multiple step tests.

It can be seen, that the minimum creep strain rate of the single step test at 150MPa is more than 300-times lower compared to the minimum creep strain rate in multiple step test and single step test with pre-aged specimen at the same stress level. Furthermore the test data of the multiple step test and test with pre-aged specimens show a very similar behaviour. Therefore the time at test temperature determines the minimum strain rate independent of strain in alloy AlCuBiPb (Figure 5 and 6).

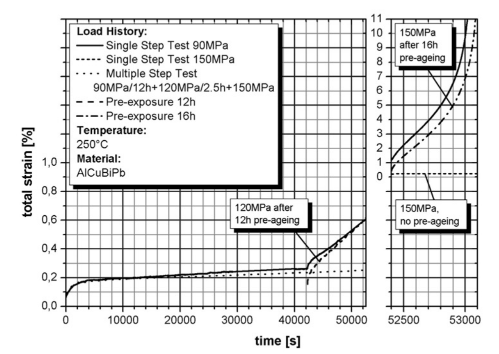


Figure 5: Comparison of creep curves with pre-ageing and multiple step test

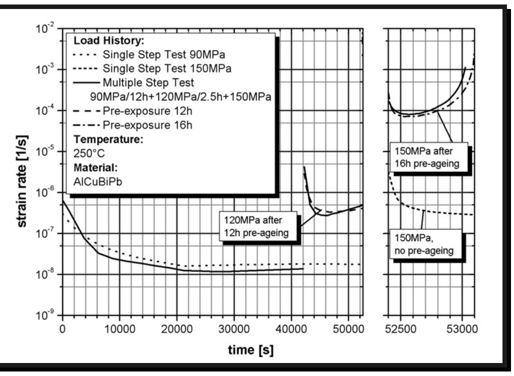


Figure 6: Comparison of creep strain rates in single step test with pre-ageing and multiple step test

4 EXPERIMENTAL SETUP FOR TMF-TESTING

The out-of-phase TMF tests are performed with a minimum temperature of T_{min} = 40 °C and varying maximum temperatures from T_{max} = 200 °C up to 300 °C. In the first testing machine (method 1) the specimen is clamped between two water-cooled grips within a stiff load frame containing a high-resolution load cell. The temperature is measured by a K-type sheath-thermocouple situated directly inside the testing cross section of the hollow drilled specimen. The strain is also measured directly in the parallel length of the gauge section. This method of measuring temperature in axial and radial symmetric position and strain in axial direction within the investigated parallel testing cross section minimises possible inaccuracies due to additional transfer functions (Riedler [3]). Heating is performed by a high frequency induction heating system with a planetoid coil, where the temperature is constant over a wide range. Cooling is performed by water-cooled grips. A temperature controller and a data acquisition system with superior control functions complete the first test rig.

The setup in the second testing machine (method 2) is similar to the first method described above. The only difference is an additional servo-hydraulic cylinder with a closed loop strain control. Again the strain is measured directly within the parallel cross section of the specimens. Therefore any mechanical strain amplitude can be simulated with this test rig.

Eqn 2 introduces the factor K_{TM} to describe the total mechanical strain. K_{TM} is defined as the ratio between total mechanical strain amplitude and thermal strain amplitude:

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

5 EXPERIMENTAL RESULTS OF TMF-TEST

Two different out-of-phase TMF conditions were tested on the servo-hydraulic test rig:

- Ideal OP-TMF situation, $\varepsilon_{t,mech}=-\varepsilon_{th}$, $K_{TM}=1$
- Overcompensation of thermal strains, $\varepsilon_m=-2*\varepsilon_{th}$, $K_{TM}=2$

In Figure 7 the results are compared to the results of testing method 1 with rigid clamped specimens. There the factor K_{TM} is not constant during the test, because the material softening due to ageing leads to higher local strains. Therefore $\underline{K}_{TM}$ at half lifetime is listed in the diagram below.

For high temperatures K_{TM} becomes greater than 2 in testing method 1. Therefore the numbers of cycles to failure are a little lower than in the testing method 2 with a constant K_{TM} of 2 for the duration of the experiment. For lower temperature amplitudes K_{TM} is about 1.1, when testing a rigid clamped specimen. This is the lower limit for K_{TM} with only elastic deformation within the parallel cross section using testing method 1.

Because dwell times have an important influence on the lifetime behaviour [Riedler [4]), all experiments were conducted with a dwell time of 24 seconds.

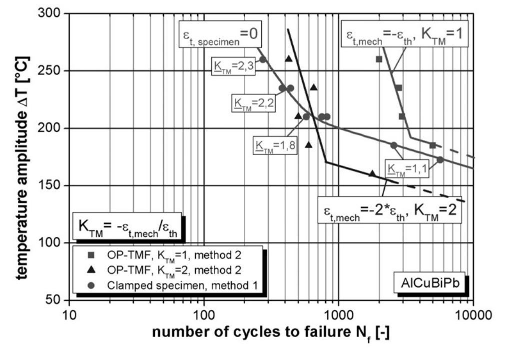


Figure 7: Comparison of different OP-TMF tests

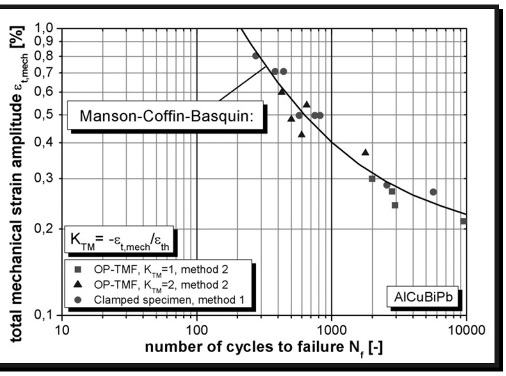


Figure 8: Description of the lifetime-behaviour using Manson-Coffin-Basquin-approach

When the local strains are taken into account in method 1, all testing results can be drawn together (Figure 8) and described with the simple Manson-Coffin-Basquin approach (Manson [5], Coffin [6], Basquin [7]):

$$\varepsilon_{t,mech} = \varepsilon_f'(N_f)^c + \frac{\sigma_f'}{E}(N_f)^b$$

6 FINITE ELEMENT STUDIES

The local effects in the specimens during TMF-testing were studied using FE analysis with a nonlinear kinematic material model. The results of the specimen according to method 1 show high local strains within the parallel testing cross section of the specimen.

With the results of the FE-analysis two effects in the clamped specimen (method 1) can be extracted: On the one hand, the stresses in the outer region of the specimen are much smaller compared to the stresses in testing section. In addition the lower temperatures in this region lead to higher yield stresses. On the other hand the thermal strains are reduced. 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.

As a result the temperature distribution (cooling condition and coil geometry) and the geometry of the specimen affect the factor K_{TM}.

Using a servo-hydraulic testing system with closed loop control of local measured strain allows to test the ideal rigid restraint condition (method 2, K_{TM}=1), because the effects of specimen geometry and temperature distribution are eliminated.

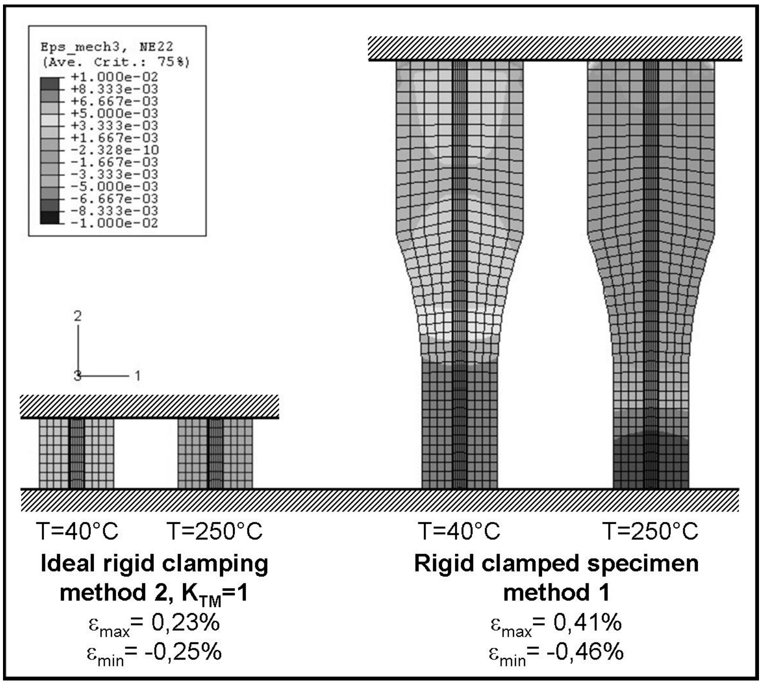


Figure 7: Comparison of method 2 using a servo-hydraulic testing machine and method 1 in OP-TMF testing

7 CONCLUSION

Ageing phenomena dominate the creep behaviour of the investigated alloy AlCuBiPb. Therefore the complete time-temperature-history must be taken into account, independent of the loading.

The simple test of a clamped specimen under out-of-phase TMF loading gives an idea of the complex phenomena in TMF loaded components. The material behaviour is dependent on time, temperature, strain rate and accumulated plastic strain. Therefore the mechanical strain amplitude is not constant during service life, although the temperature amplitude is not changed. For a simple life time calculation an average $\underline{K}_{TM}$ can be used, to calculate the total mechanical strain amplitude. Using the simple Manson-Coffin-Basquin approach, the number of cycles to failure can be estimated.

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