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THERMO-MECHANICAL FATIGUE TESTING: METHODS OF CONDUCTING TESTS AND MEASURING THE MATERIAL BEHAVIOUR

Two different principles of TMF-testing were investigated for the wrought aluminium alloy AlCuBiPb (2011). In the first testing method the specimens are clamped in a stiff load frame. A cyclic temperature load is applied, which leads to an out-of-phase (OP) TMF loading. The local strain is measured within the parallel cross section of the specimen. The second series of OP-TMF tests are conducted using closed loop strain control on a servo-hydraulic TMF testing system, which guarantees a rigid restraint condition within the parallel section of the specimen. To compare these two principles of TMF-testing, additional experiments were conducted with different mechanical strain amplitudes. The two experiments can be compared well, when the local strains are taken into account. Therefore, the method of the rigid clamped specimen can be used to get experimental data in a wide range of strain amplitudes.

1. Introduction

The description of the thermo-mechanical fatigue (TMF) behaviour of engine components made form aluminium alloys is an important design step in the automotive industry. The steady rise of engine power and the demand for lightweight construction with an enhanced reliability require an optimised dimensioning process. In order to improve the methodology for simulating the fatigue behaviour of thermo-mechanically loaded engine components,

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basic experiments are carried out in order to describe the overall thermo-mechanical-fatigue behaviour.

Many different methods in testing thermo-mechanical fatigue can be found in the literature: expensive component tests, simple specimens' tests to compare materials and complex TMF-test on servo-hydraulic testing systems [1], [2], [3], [4], [5]. An additional problem is a missing standard in the field of TMF-testing. The results can be influenced by the testing method used and are sensitive to the heating system and temperature control. Additionally, strain and temperature measurement is a challenge within the field of TMF-testing.

The complex material behaviour of aluminium alloys is dependent on temperature and accumulated plastic strain. At high temperature the strain rate has a considerable influence on the stress-strain-behaviour [6]. In most of the aluminium alloys, precipitation hardening is responsible for the strength of the material. Due to coarsening, these strengthening mechanisms loose their effects [7] during high temperature applications above approx. 423 K. Therefore, the local mechanical strain amplitude during TMF-loading can vary with time, when ageing effects are playing an important role. Eqn. 1 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:

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

The disadvantage of the definition above is the missing algebraic sign. To avoid this problem, an extended definition is suggested in equation 2. This definition gives positive values for K_{TM} in out-of-phase TMF loading and negative values for in-phase loading.

$$K_{TM} = \frac{\varepsilon_{T=T\max}^{mech} - \varepsilon_{T=T\min}^{mech}}{\alpha_{th} \cdot \Delta T} \tag{2}$$

All tests have been conducted for wrought aluminium alloy AlCuBiPb (2011). Tab. 1 shows the chemical composition of the alloy. This material shows high values for tensile stress and fracture elongation at room temperature in the heat treated condition.

During high temperature application, the material looses its strength due to ageing processes (see Fig. 1).

Table 1.

Chemical composition for Al-2011

	Cu	Bi	Pb	Fe	Mg	Si	Zn	Al
AlCuBiPb	0.32	0.05	0.78	0.32	0.82	0.31	0.03	bal.

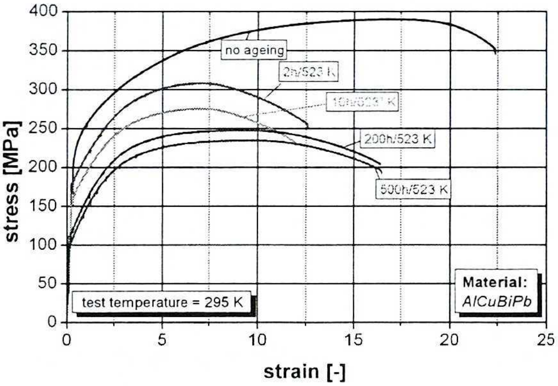

Fig. 1. Influence of artificial ageing on the stress-strain-behaviour of AlCuBiPb

2. Experimental setup for TMF-testing

The out-of-phase TMF tests are performed with a minimum temperature of $T_{min} = 313$ K and varying maximum temperatures from $T_{max} = 473$ K up to 573 K. 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 (Fig. 2).

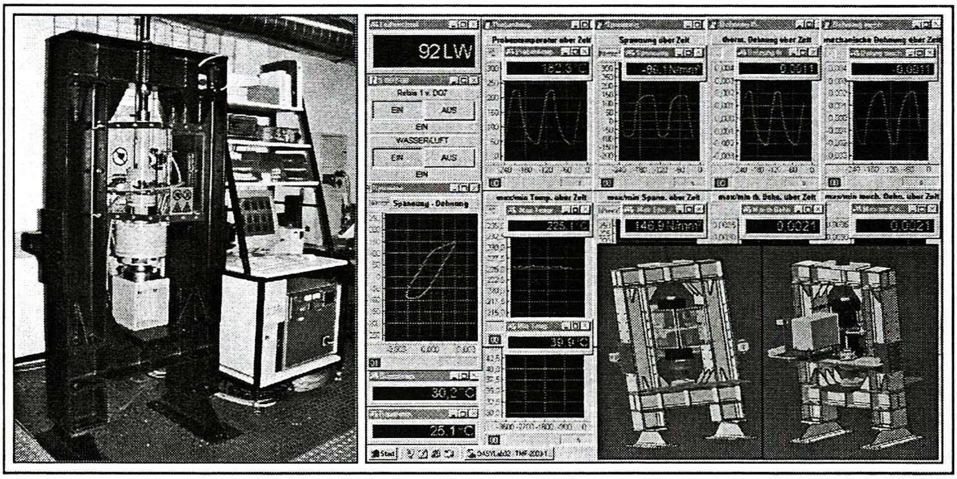

Fig. 2. TMF testing system of a rigid clamped specimen (method 1)

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 [8]). 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, Fig. 3) is similar to the first method described above. The only difference is an additional servo-hydraulic cylinder with a closed loop control. The complete control system was realised using a fast industrial programmable logic controller (PLC). Beside different functions for the manual mode of the test rig, different program modules were added to allow a maximum flexibility in testing. Beside TMF-tests it is possible to conduct LCF- and HCF-tests at any temperature and cyclic stress relaxation tests. Thermal strain compensation is included to avoid transient heat effects during fast heating. Superimposed high cycle fatigue loading during the TMF-cycle can be tested, too.

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.

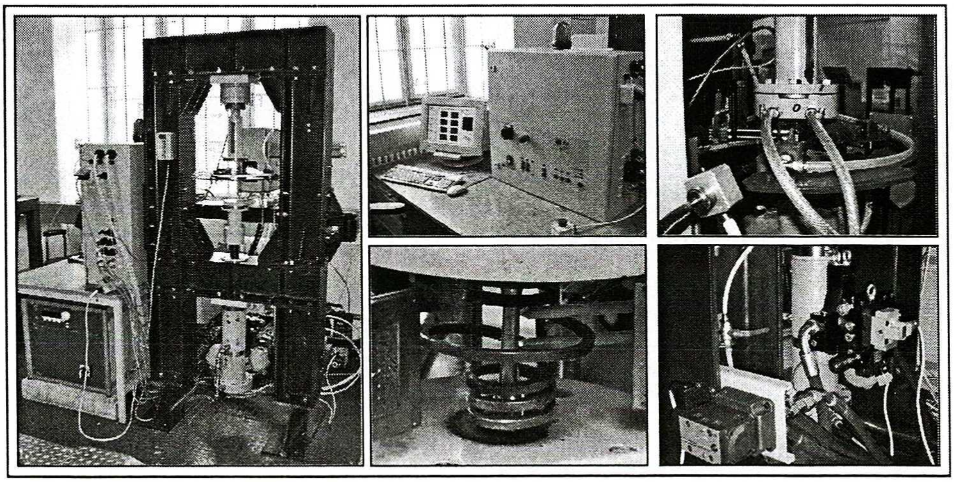

Fig. 3. Servo-hydraulic TMF testing system (method 2)

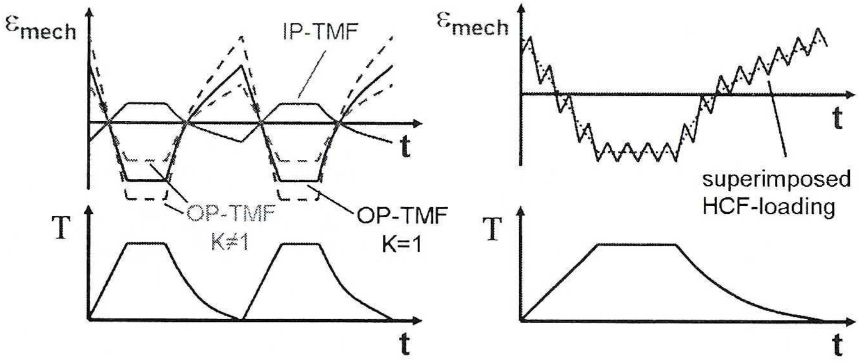

Fig. 4. Possible TMF-load cases

The following tests are only possible using closed loop strain control (Fig. 4):

- OP-TMF with a constant ration between thermal and mechanical strain
- OP-TMF in the over or under constrained condition ($K_{TM} > 1$ and $K_{TM} < 1$)
- In-Phase TMF tests (IP-TMF)
- TMF with superimposed high cycle fatigue loading (TMF + HCF)

3. Finite element studies

The geometry of the specimen was simulated using the commercial finite element software ABAQUS®.

The following assumptions were made for the FE-calculations (see Fig. 5):

- The FE-mesh was modelled rotationally symmetrical using CAX8-elememts. Therefore the drilled hole is assumed to be perfectly centrically.
- The temperature distribution measured in the experiment was cycled as a linear ramp between the maximum and minimum temperature.

The following boundary conditions were used:

- The specimen is fixed in axial direction at the clamped ends.
- The condition of ideal rigid clamping was simulated by fixing the parallel cross section of the specimen at the gauge length of the extensometer used.

A temperature dependent, non-linear kinematic material model was used in the calculations. The material constants were determined from low cycle fatigue tests and tensile tests. The material behaviour was tested in single-element calculations, small adjustments in the material properties lead to further improvements of the material behaviour.

During the dwell time at maximum temperature stress relaxation effects occur. To consider these effects, creep has to be taken into account within the finite element calculation. Therefore, a temperature dependent Norton-law is used. For the alloy AlCuBiPb these properties have already been published in [10].

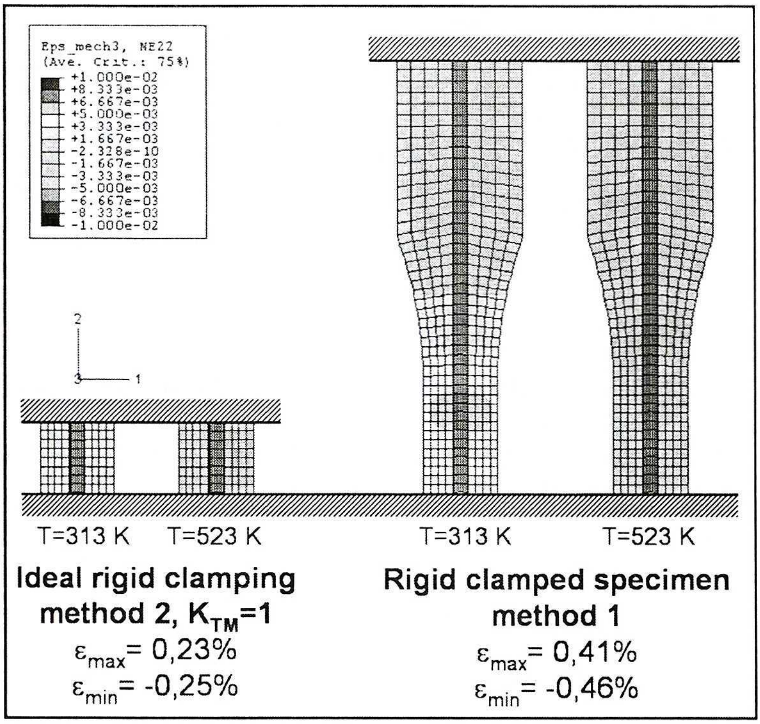

Fig. 5. Results of FE-simulation: comparison of method 2 and method 1

The results show that high local strains occur within the parallel cross section of the rigid clamped specimen (Fig. 5). The thermal strains are overcompensated; the value of K_{TM} can be estimated with 2.0. Therefore, it is essential to monitor and record the local strains in this testing method.

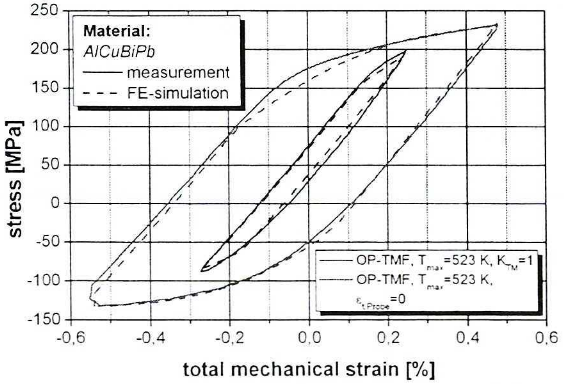

Fig. 6. Calculated TMF-Hysteresis loops compared to experimental data

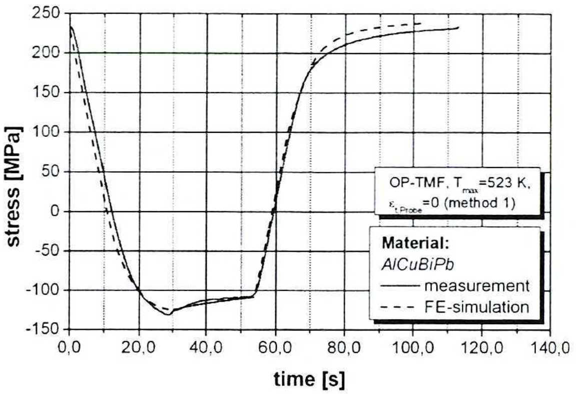

Fig. 7. Stress-time history for rigid clamped specimen in TMF-test with maximum temperature 573 K

The calculated stress-strain hysteresis loops (Fig. 6) and the stress history (Fig. 7) can be calculated very accurately.

Conclusions of the FE-calculations:

- Local strains occur during the test of a rigid clamped specimen.
- Because the local strains depend on the temperature distribution, the mechanical strain amplitude depends also on coil geometry, cooling system and geometry of the specimen.
- Furthermore, the local strains are dependent on the cyclic material properties. Therefore, the mechanical strain amplitude depends on hold times (due to ageing of the material) and accumulated plastic strain (number of cycles).

4. Experimental results

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

- ideal OP-TMF situation, $\varepsilon_{t,\mathrm{mech}} = -\varepsilon_{\mathrm{th}}$, $K_{TM} = 1$,
- overcompensation of thermal strains, $\varepsilon_{m} = -2 * \varepsilon_{\mathrm{th}}$, $K_{TM} = 2$.

The minimum temperature was generally 313 K; a maximum temperature between 473 K and 573 K was used in the tests. In testing method 1, tests were performed using maximum temperatures between 485 K and 573 K. Because dwell times have an important influence on the lifetime behaviour [Riedler [9]), all experiments were conducted with a dwell time of 24 seconds (Fig. 8).

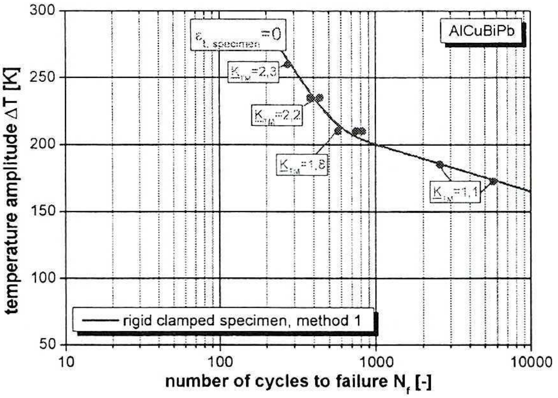

Fig. 8. Cycles to failure in the test of rigid clamped specimens (method 1)

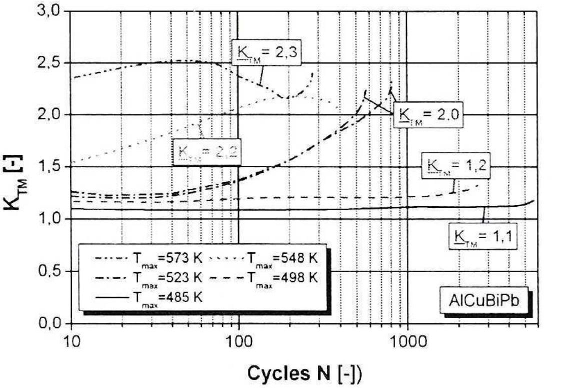

Fig. 9. Time dependent K_{TM} because of material softening due to ageing phenomena

Due to ageing processes within the specimen and cyclic softening, K_{TM} is not constant during the test of a rigid clamped specimen. The softening of the material leads to higher local strains, therefore K_{TM} increases during the test. To compare the results, K_{TM} was used at the half number of cycles to failure ($\underline{K}_{TM}$), Fig. 9.

In Figure 10 the lifetime results are compared to the results of testing method 1 with rigid clamped specimens. For high temperatures K_{TM} becomes greater than 2 in testing method 1. Therefore, the number of cycles to failure is 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.

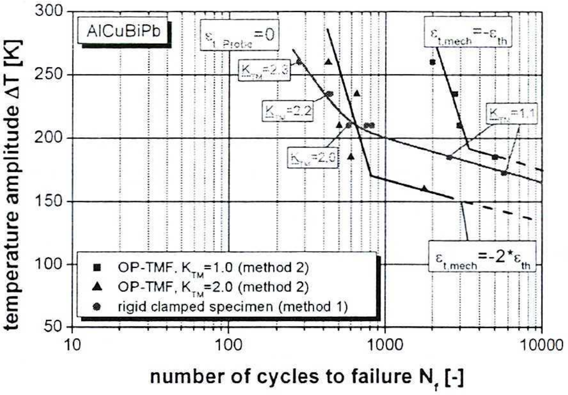

Fig. 10. The results of the servo-hydraulic TMF-tests agree well with the data of the rigid clamped specimen

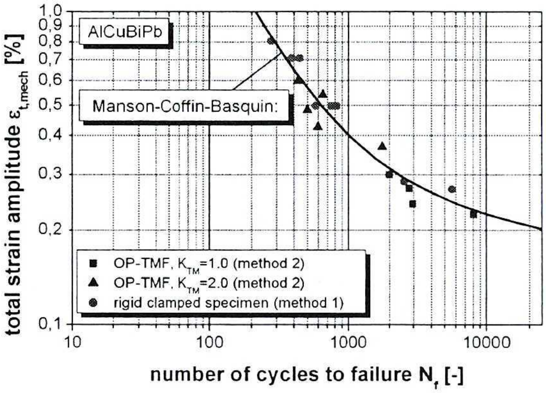

Fig. 11. All results can be described using the Manson-Coffin-Basquin approach

When the local strains are taken into account in testing method 1 (rigid clamped specimen), all results can be drawn together in a strain vs. cycles to failure diagram (Fig. 11). The data points can be described well using the well known Manson-Coffin-Basquin [11], [12], [13] approach (equation 1).

$$\varepsilon_{t,mech} = \varepsilon_f'(N_f)^c + \frac{\sigma_f'}{E}(N_f)^b \qquad (2)$$

The parameters are given in the following table:

Ductility coefficient	ε_f'	151.4
Ductility exponent	c	−1.0
Fatigue Strength/E-Module	σ_f'/E	0.493
Fatigue ductility	b	−0.095

5. Conclusion

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 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. TMF-tests using closed loop strain control show a good correlation with the test of the rigid clamped specimen. For the modelling of the material behaviour this tests are much more useful, because the calculations can be done in a single element.

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Badanie zmęczenia termomechanicznego: Metody prowadzenia testów i pomiary właściwości materiału

Streszczenie

Badano dwie różne metody termomechanicznych testów zmęczeniowych (TMF) dla stopów aluminiowych do obróbki plastycznej AlCuBiPb (2011). W pierwszej z badanych metod próbki materiału są mocowane w sztywnej ramie obciążeniowej. Stosuje się cykliczne obciążenie temperaturowe, które wywołuje niezsynchronizowane fazowo obciążenie termomechaniczne (OP TMF). Lokalne naprężenia są mierzone w obrębie równoległego przekroju próbki. W drugiej z przeprowadzonych serii testów OP TMF zastosowano zamkniętą pętlę sterowania naprężeniem w systemie serwomechanizmu hydraulicznego do termomechanicznych badań zmęczeniowych, co gwarantowało sztywne spełnienie warunku granicznego w równoległym przekroju próbki. Aby porównać dwie wymienione zasady testów TMF przeprowadzono dodatkowe eksperymenty przy różnych amplitudach naprężeń mechanicznych.

Obydwa eksperymenty dają porównywalne wyniki, gdy uwzględni się naprężenia lokalne. Metoda, w której próbki mocuje się w sztywnej ramie, może więc być użyta dla uzyskania danych eksperymentalnych w szerokim zakresie amplitud naprężenia.