Cyclic stress-strain behaviour under thermomechanical fatigue conditions – Modeling by means of an enhanced multi-component model

H J Christ¹ and V Bauer²

¹ Institut für Werkstofftechnik, Universität Siegen, D-57068 Siegen, Germany
² Wieland Werke AG, Graf-Arco Str. 36, D-89072 Ulm, Germany

Abstract. The cyclic stress-strain behaviour of metals and alloys in cyclic saturation can reasonably be described by means of simple multi-component models, such as the model based on a parallel arrangement of elastic-perfectly plastic elements, which was originally proposed by Masing already in 1923. This model concept was applied to thermomechanical fatigue loading of two metallic engineering materials which were found to be rather oppositional with respect to cyclic plastic deformation. One material is an austenitic stainless steel of type AISI304L which shows dynamic strain aging (DSA) and serves as an example for a rather ductile alloy. A dislocation arrangement was found after TMF testing deviating characteristically from the corresponding isothermal microstructures. The second material is a third-generation near-gamma TiAl alloy which is characterized by a very pronounced ductile-to-brittle transition (DBT) within the temperature range of TMF cycling. Isothermal fatigue testing at temperatures below the DBT temperature leads to cyclic hardening, while cyclic softening was found to occur above DBT. The combined effect under TMF leads to a continuously developing mean stress. The experimental observations regarding isothermal and non-isothermal stress-strain behaviour and the correlation to the underlying microstructural processes was used to further develop the TMF multi-composite model in order to accurately predict the TMF stress-strain response by taking the alloy-specific features into account.

1. Introduction

Engineering components and structures that operate at elevated temperatures, e.g. in electric power generation equipment, gas turbines or chemical reactors, are often subjected not only to isothermal cyclic or static loading but also to thermal transients during start-up and shut-down stages resulting in plastic deformations in the highly stressed regions. In many high-temperature applications this combination of cyclic thermal loading and cyclic mechanical loading leads to thermomechanical fatigue (TMF) and may even be considered to be the primary life-limiting damage contribution. In laboratory testing, most commonly TMF tests are carried out (in addition to isothermal LCF tests) applying the two extreme TMF modes of in-phase (IP) and out-of-phase (OP) temperature-strain phasing.

The present study deals with the cyclic stress-strain response under TMF loading conditions and the description of this behaviour by means of material-specific expansions of a simple multi-component model. Two extremely different metallic materials, an austenitic stainless steel of type AISI304L and a third-generation near-γ TiAl alloy (in duplex condition), were selected, in order to illustrate the broad...
variety of TMF-induced changes as compared to isothermal LCF. A reliable simulation of the non-isothermal stress-strain path is a valuable contribution to many TMF life prediction methods. More details on this aspect and information on the materials studied and the experimental techniques applied can be found in [1-4].

2. Application of Masing’s model to thermomechanical fatigue

It has been shown in an earlier work [5] that the so-called pseudo-isothermal thermomechanical fatigue behaviour (PITMF behaviour) can be calculated from the hysteresis loops of isothermal fatigue tests performed at different temperatures by applying a multi-component model originally proposed by Masing [6]. The basic assumption of this model is that a material consists of a parallel arrangement of elements which deform in a linear elastic-perfectly plastic manner. The distribution of the element-specific yield stresses $\sigma_y$ of the elementary volumes is expressed by means of a yield stress distribution density function $f_p(\sigma_y)$ which can be determined from a single branch of a hysteresis loop.

The stress-strain path can easily be calculated on the basis of the second integral function $G_p(\sigma_y)$ of $f_p(\sigma_y)$ or by using the model in a discretised manner (e.g. on the basis of 30 elementary volumes). In the case of anisothermal conditions, the effect of temperature on the yield stress distribution density function must be included and the calculation is carried out in small strain and temperature increments. PITMF behaviour means that the material is assumed to behave under varying temperature at each temperature as it does in the corresponding isothermal test. Hence, it defines a reference behaviour which helps to identify TMF-specific deformation features on the basis of a comparison of the simulation result and the experimental observation.

3. Stress-strain behaviour of the austenitic stainless steel

The isothermal LCF behaviour of AISI304L is strongly affected by the occurrence of dynamic strain aging (DSA) in an intermediate temperature range between 250°C and 500°C. DSA manifests itself in a change of the saturation dislocation arrangement, as clearly seen in figure 1. Both, at low and high temperatures a cell or subgrain dislocation arrangement forms, whereas a disorderly planar-type arrangement was observed in an intermediate temperature range. The more planar dislocation slip of DSA increases the saturation stress amplitude at constant plastic strain amplitude (figure 2).

Figure 1. Dislocation arrangement of isothermal fatigue tests at different temperatures and a plastic strain amplitude of 0.5%.

Figure 2. Calculated and measured hysteresis loops of two IP TMF tests compared to the isothermal saturation stress amplitude.

Figure 2 shows the measured and the calculated (PITMF) hysteresis loops for two IP tests together with a representation of the saturation stress amplitudes of isothermal tests vs temperature. Peak and valley stresses of the calculated loops correspond very nicely to the saturation stress amplitude values $\sigma_{sat}$ of the respective isothermal test. However, outside the temperature range of DSA, the load reversal points of the experimentally observed loops deviate significantly from the $\sigma_{sat}$ course. The impeded
dislocation mobility in the DSA region strongly affects the adjusting TMF dislocation arrangement and leads to higher strength both at higher and lower temperature.

Additional tests were carried out with temperature changes from the saturation state within the DSA regime to a temperature above or below the DSA temperature range. Figure 3 shows the cyclic deformation curve of a test, during which the temperature was changed from 500°C (inside the DSA regime) to 250°C (above DSA), and compares the stress amplitude with the values from isothermal testing at 250°C. The strengthening effect of predeformation in the DSA temperature range is clearly visible. This effect can be incorporated into the stress-strain response modeling by using the yield stress distribution density function from hysteresis loops obtained in respective temperature change tests instead of those from loops of isothermal tests (without pre-cycling in the DSA regime). Figure 4 compares the hysteresis loop of cyclic saturation of an IP test with the predicted hysteresis loop documenting a reasonable agreement. For higher maximum temperatures, low strain rates and superimposed dwell times creep and stress relaxation has to be taken additionally into account in the model.

![Figure 3. Comparison of the stress response during a temperature change test (500°C → 250°C) with the isothermal response at 250°C.](image1)

![Figure 4. Comparison of a measured hysteresis loop of a IP test with a calculated loop considering the DSA prehistory.](image2)

### 4. Stress-strain behaviour of the third-generation near-γ TiAl alloy

Isothermal fatigue tests performed on the near-γ TiAl alloy studied showed a rather pronounced cyclic saturation independent of testing temperature. However, a more detailed analysis of the course of the plastic strain amplitude in the total-strain-controlled tests revealed a slight cyclic hardening for T < 550°C and cyclic softening at T > 650°C. As a consequence of this behaviour a continuously developing mean stress σ_m results under TMF conditions, while the stress amplitude Δσ/2 remains fairly constant (see figure 5 and 6).

![Figure 5. Development of stress amplitude and mean stress with number of cycles for three in-phase TMF tests at a mechanical strain amplitude of 0.6%.](image3)

![Figure 6. Development of stress amplitude and mean stress with number of cycles for three out-of-phase TMF tests at a mechanical strain amplitude of 0.6%.](image4)
In order to model this TMF mean stress development, simple power-law equations were deduced from the isothermal cyclic-deformation curves. In the calculation of the cyclic stress-strain response of TMF, cyclic softening and hardening was iteratively considered cycle by cycle at the maximum and minimum temperature, respectively. For this purpose the isothermal softening/hardening response was applied to the corresponding peak and valley stresses calculated by means of the multi-component model in the first instance. This procedure is schematically shown in figure 7, which also compares the predicted and the experimentally observed mean stress values. In figure 8 the hysteresis loops of IP TMF loading with a temperature range of 500-750°C are shown for the second cycle and the cycle at half life $N_f/2$ and compared with the corresponding results from the simulation. As a consequence of the similarity in the deformation processes during isothermal and thermomechanical cyclic deformation the predicted results for the first few cycles coincide well with the measured loops. With advancing number of cycles the negative mean stress during IP testing decreases and the hysteresis loop shifts downwards. This shift is reasonably predicted on the basis of the isothermal softening and hardening behaviour.

5. Conclusions
Both materials studied show a cyclic stress-strain behaviour under TMF conditions that deviates characteristically from that observed under isothermal conditions. This phenomenon can be attributed to the occurrence of dynamic strain aging in the case of AISI304L, while cyclic hardening and softening of the TiAl alloy at low and high temperatures, respectively, lead to a continuously developing mean stress at varying temperature. The multi-component model (i) helps to identify the TMF-specific behaviour and (ii) can easily be expanded in such a way that these effects are considered.

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