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Is Thermomechanical Fatigue Life Predictable?

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Abstract

Throughout the world, extensive low-cycle fatigue (LCF) data, which is traditionally used for design purposes, has been generated isothermally on various high-temperature materials, and thus, it is tempting to try to predict TMF life based mainly on isothermal LCF data. In this contribution, studies on different metallic structural high-temperature materials, which have been carried out in the author's laboratory, are reviewed addressing the question, in which way and to which extent a reliable, unerring and robust TMF life assessment is possible on the basis of isothermally obtained fatigue life data. It is shown by means of examples that a sound TMF life prediction requires a detailed mechanistic understanding of both the non-isothermal cyclic stress-strain response and the TMF-specific damage evolution.

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1. Introduction

Thermomechanical fatigue (TMF) is the primary life-limiting factor for engineering components in many high-temperature applications. For example, during the transient regimes of start-up and shut-down operations, blades in gas turbines are submitted to low-cycle TMF due to the temperature gradients generated caused by temperature variations often in combination with internal air cooling. Depending on the location of the volume element considered and the cooling situation, various types of strain-temperature phasing can arise. In laboratory testing most commonly the two extreme cases, in-phase (IP) and out-of-phase (OP) TMF, are studied.

Due to the life-reducing effect of TMF it is important to investigate the TMF behaviour of engineering materials in order to model thermomechanical fatigue life correctly. On the other hand, for many structural materials extensive, isothermally determined low-cycle fatigue (LCF) data has been generated at various temperatures, and thus, it would be very efficient, if TMF life could be predicted based largely on isothermal LCF data. However, it is well known that depending on the actual loading conditions damage can evolve differently [1,2], and life prediction may well be non-conservative if the relevant damage mechanisms are not captured accurately. Still, studies that assess the predictive capabilities of TMF life models [1-10] are rare. Part

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of this results from the large number of model parameters that need to be determined for the more advanced life models. Given this scenario, the objective of the present study is to answer the question, whether TMF life can in principle be considered to be predictable from isothermally obtained data. Furthermore the requirements with respect to material behaviour and knowledge base are considered which have to be fulfilled to allow for the development of TMF life models that are robust, easily implemented, and do not require sophisticated testing.

This paper is based on the results which have been obtained in various studies on the TMF behaviour of structural metallic materials in the author’s laboratory during almost two decades. Selected results are presented in order to illustrate exemplarily the broad spectrum of phenomena. After showing the strong effect of temperature on the isothermal cyclic stress-strain behaviour and the damage mechanisms, some peculiarities resulting from the varying temperature of TMF are illustrated. Then it is documented that TMF life prediction requires cyclic plasticity meaning that the stage of crack propagation must strongly contribute to cyclic life. Finally the need of a close correlation of the relevant damage mechanism and the suitable damage parameter is verified.

2. Materials and some experimental details

This study reports on the behaviour of four different materials which were investigated in the framework of Ph.D. works [11-14]. An AISI 304 L-type stainless steel was used, as a large amount of data generated on this material in isothermal LCF tests, creep-fatigue tests and TMF tests are available. The second material chosen was X8019+12.5SiCp that is a dispersion-strengthened SiC particulate-reinforced aluminium alloy (matrix composition: Al-8Fe-4Ce, in wt pct). Within the matrix, fine and thermally very stable dispersoids with a high volume fraction of 0.23 are present. The dispersoids provide for excellent creep properties at elevated temperatures. The reinforcement with 12.5 vol. pct SiC particulates increases both the elastic modulus and the fatigue crack growth threshold of the alloy. As the third material the high-temperature titanium alloy IMI 834 was applied which is a near-α Ti alloy of nominal composition Ti-5.8Al-4.0Sn-3.5Zr-0.7Nb-0.5Mo-0.35Si-0.06C (in wt pct). All data used in this study was obtained on the bimodal microstructure which is designed to yield an optimum compromise between creep and fatigue performance. The third generation near-γ TiAl alloy used in this study as fourth material was produced by Plansee AG, Austria with a nominal composition of Ti-47Al-5.1Nb-0.25C-0.4B (at pct). In order to obtain the duplex microstructure desired, the material was subjected to a solution treatment at a temperature of 1270 °C for 45 minutes and subsequently furnace cooled at a cooling rate of approximately 5 K/min. The Ductile to Brittle Transition Temperature (DBTT), which is a significant quantity for TiAl alloys, was determined for the alloy considered to be about 750 °C. The transition from brittle to ductile behaviour manifests itself in a strong increase in fracture ductility when exceeding the temperature of 750 °C because of the onset of dislocation climb.

In all cases, the isothermal fatigue (IF) and TMF tests evaluated were selected such that a wide range of test parameters were covered. The TMF tests were of in-phase and out-of-phase type, i.e. maximum test temperature coincided with maximum strain (in tension) or minimum strain (in compression), respectively. All tests except of those on the γ-TiAl alloy were conducted in true-plastic-strain control, and a triangular wave form was used for the command signal. Because of the brittleness of the TiAl alloy, total-strain control had to be applied in this case.

3. Results and discussion

3.1 Isothermal fatigue mechanisms

It is well-known and has been studied in detail that the cyclic deformation mechanism depends strongly on temperature applied in IF. Figure 1 tries to summarize some of these effects. While at low temperature dislocations motion is dominated by gliding, dislocation climb gains importance with increasing temperature. Most of the metallic materials show a strong interaction of point defects with moving dislocations giving rise to dynamic strain aging (DSA). The cyclic deformation response of a material can be affected via
dislocation/microstructure interactions by microstructural changes resulting from phenomena such as deformation-induced transformation (e.g., martensite formation in metastable austenitic stainless steels), mechanical twinning (e.g., in intermetallic phases), deformation-induced precipitation (e.g., in solution-annealed alloys) and coarsening (e.g., in precipitation-strengthened materials).

Fig. 1. Effect of temperature on cyclic stress-strain behaviour.

Fig. 2. Effect of temperature on damage mechanism.

A similar strong dependence on temperature exists for the dominant damage mechanism which is responsible for isothermal fatigue life of a material. Figure 2 represents a small selection of possible mechanisms. With increasing temperature a shift from cycle-dependent damage to time-dependent damage occurs. The last one is mainly a consequence of environmental effects and creep. Some materials are known to be prone to specific damage contributions such as hydrogen effects in the case of titanium alloys at moderate temperatures or dynamic embrittlement, often also termed stress-assisted grain boundary oxidation (SAGBO), of polycrystalline Ni-base superalloys.
As a prominent example for a temperature influence, the effect of DSA on cyclic stress-strain response and fatigue life $N_f$ of AISI 304 L is shown in Fig. 3 [15]. DSA leads to an increase of the maximum and saturation stress amplitude in an intermediate temperature range observed in tests carried out at a constant plastic strain amplitude of 0.5 pct. As a direct consequence of this stress amplitude raise the cyclic life drops in the corresponding temperature range before creep damage reduces $N_f$ further.

Figure 4a and 4b [8] show typical examples for crack initiation sites as observed on IMI 834 after cyclic deformation at low and high temperature, respectively. Up to a testing temperature of about 400°C, most cracks are formed within the primary α grains (Fig. 4a). At higher magnification, it becomes apparent that cracks initiate along planar slip bands. The few fatigue cracks which were found in the primary α grains at T=600 °C seem to become non-propagating as soon as they reach the grain boundary. The cracks form in the transformed α grains (the prior β grains) and seem to grow unhindered (Figure 4b). A possible explanation for this change in the crack initiation mechanism is a transition in slip mode from planar to wavy which occurs at around 600 °C.

![Fig. 3. Effect of dynamic strain aging on (a) the stress amplitude of isothermal fatigue tests at a plastic strain amplitude of 0.5 pct and (b) the corresponding number of cycles until failure in air and vacuum [15].](image)

![Fig. 4. SEM micrographs showing typical crack initiation sites for tests run at (a) T=400 °C and (b) T=600 °C (stress axis is horizontal) [8].](image)

The considerations and supporting examples shown in this chapter clearly demonstrate that before dealing with TMF a sound understanding of the isothermal behaviour has to be developed. This behaviour forms the
reference related to which the effects arising from the varying temperature of TMF can be identified. Hence, this sound basis obtained from extensive isothermal testing is a must for any rational consideration of TMF.

3.2 Specifics of TMF

From the representations shown in Fig. 1 and Fig. 2 it becomes evident that a continuously changing temperature can easily lead to continuously changing dislocation slip character and damage mechanism. Since temperature is varying periodically within a temperature range during TMF loading, a key issue of TMF life prediction is to identify the non-isothermal cyclic stress-strain response and the corresponding most relevant damage mechanism. Fortunately, the repetitive conditions mostly lead to a situation, where at least within a cycle (i.e., within a hysteresis loop) a quasi steady state can be assumed, and the change from cycle to cycle appears to be small or is even negligible.

Two examples are presented to illustrate the specific behaviour of alloys under TMF conditions. Figure 5 shows the answer of AISI 304 L to a sudden temperature change from 400 °C to 650 °C during fatigue testing at a constant plastic strain amplitude of 0.5 pct. As mentioned above (Fig. 3) the first temperature is in the DSA regime and a planar type of dislocation arrangement is formed. The increase to 650 °C leads to a stress amplitude which is significantly higher than the corresponding stress amplitude of the isothermal test at this temperature (dashed line). Therefore, it can be concluded that the dislocation arrangement formed after the temperature change is strongly affected by the DSA prehistory. The consequence of this observation is that if TMF modelling deals with conditions where the DSA temperature range is passed through the required stress-strain data should be determined in temperature-change tests instead of IF testing (see details in [15]).

In the case of the near-γ TiAl alloy a very stable microstructure was observed in the temperature range of interest. Consequently the isothermal fatigue behaviour is characterized by a pronounced cyclic saturation. This holds also true under TMF conditions with respect to the stress amplitude. However, a mean stress develops continuously as seen in Fig. 6 for OP-TMF. The non-isothermal conditions leads to cyclic softening at high temperatures and (slight) cyclic hardening at low temperatures resulting in a mean stress in OP and IP testing which is positive (tensile) and negative (compressive), respectively. In particular the positive mean stress developing during OP conditions strongly deteriorates TMF life.
As a part of the answer to the basic question of TMF life predictability addressed in this paper the conclusion from these (and many other existing) examples is that a thorough study of the specifics of TMF is indispensable in order to select the suitable approach for TMF life assessment. Hence, at least some TMF tests must be carried out, and the testing parameters should be chosen in such a way that they match the service conditions closely.

3.3 Requirement of cyclic plasticity

Most of the models reported in the literature, which are used for TMF life prediction, are connected in some way to the hysteresis loop or the deformation energy density. This holds true for many empirical approaches but also for most fracture mechanics concepts suitable for high temperatures. An application of these concepts does not make sense, if the material considered behaves brittle. Brittle behaviour is in this context synonymic to a negligible fraction of life spent in crack propagation, and hence the stage of crack initiation is more important. Unfortunately, crack initiation is a very complex process starting from an atomic level, and despite much research effort the process still detracts from a mechanism-based and quantitative description.

Fatigue life results under TMF loading conditions are compared with isothermal fatigue life data in Fig. 7 for the near-\(\gamma\) TiAl alloy. TMF data is plotted as a function of the maximum temperature of the corresponding TMF cycle. The fatigue life of IP tests is approximately twice the life observed in isothermal LCF tests performed at the highest temperature of the TMF test. One reason for higher fatigue lives under IP conditions is the negative mean stress as discussed before. On the other hand, an oxide layer grows at high temperature on the specimen surface in the tension part. Apparently, the tension loading is not crucial for oxide scale cracking or spalling. For this reason cracks initiate slowly. In contrast, OP loading conditions reduce fatigue life tremendously. The fatigue life decreases at least by a factor of 5. The short TMF life in OP mode can be attributed to the accelerated oxidation-induced crack initiation during OP testing. The oxide layer mainly formed at high temperatures becomes brittle at lower temperatures. In the low temperature part of the cycle (tension) the oxide cracks easily and hence promotes crack initiation. Once formed cracks lead to failure quickly, because of the brittleness of the alloy at low temperatures (tension). A comparison of the results of the OP tests in vacuum (Fig. 7) with isothermal air tests documents that the positive mean stress shown in Fig. 6 reduces cyclic life strongly. However, the effect of environment leads to a further tremendous life reduction.
Fig. 7. Fatigue life data of the near-$\gamma$ TiAl alloy as a function of testing temperature and maximum temperature of isothermal and non-isothermal conditions, respectively [10].

Fig. 8. Comparison of predicted and observed TMF lives for tests performed in air (labelled in Fig. 7 as OP tests and IP tests); details on the model approach are given in [9].

The pronounced susceptibility of the cyclic life of the near-$\gamma$ TiAl alloy to mean stresses demands the use of a damage parameter which explicitly considers this effect. The concept of Ostergren [16] provides a simple empirical, energy-based approach, which holds true for the isothermal tests. In order to consider the effect of oxidation, temperature and frequency, an expansion of the model is necessary, which can be obtained by implementing a combination of the frequency-modified Ostergren model [17] with the oxidation damage model of Antolovich et.al. [18]. If this concept is applied to describe TMF life on the basis of the isothermal data, the match is very poor indicating that TMF damage evolution deviates strongly from the isothermal behaviour (see Fig. 8). Hence, as already stated in the beginning of this section, a sufficient ductility of the material considered is a fundamental requirement for a successful application of current TMF life prediction methodology.

3.4 Successful mechanism-based TMF life prediction

From the previous sections it should have become clear that a successful development and application of a life prediction model for TMF conditions requires a thorough experimental characterization of both the isothermal and non-isothermal fatigue behaviour of the material considered and a mechanism-based and
realistic theoretical approach with respect to damage evaluation. Unfortunately, each material has its specialties so that a generally applicable methodology cannot be expected. Rather an individual consideration which is laborious and time-consuming must be carried out. Two final examples are given in this section to shed some light on the required line of actions.

Fracture mechanics methods are a suitable means of describing fatigue life both for isothermal and thermomechanical conditions. However, the concepts must be selected carefully such that they relate closely to relevant damage mechanisms and microstructural processes. Hence, no fracture mechanics damage parameter is a priori qualified. Rather extensive testing in combination with detailed microstructural and fractographic studies must be carried out, before an appropriate concept can be selected. This approach is illustrated for the alloy X8019/12.5p in Figs. 9 and 10. Figure 9 presents a map which shows the regimes of plastic strain amplitude (ordinate) and temperature or plastic strain rate (abscissa) where damage can be attributed to fatigue, creep, oxidation or combinations of these damage types. On the basis of such a map, which resulted from metallographic inspection of correspondingly tested samples, a suitable damage parameter can be chosen and applied to the respective loading parameter regime (Fig. 10). In the case of TMF, adaptation of these concepts to non-isothermal conditions requires even more consideration in order to deduce simplifications which enable the adaptation but are also reasonable from a mechanistic point of view.
calculation. As can be seen, all data points lie within a ±2 scatter band.

Figure 11 depicts the maximum stress values observed on IMI 834 in fatigue tests in vacuum and ambient air at various temperatures as a function of the number of cycles to failure. The fatigue lives in vacuum are reasonably well predicted with the assumption of pure fatigue. The curves labeled A and B in Fig. 11 represent the calculated results for dry air and humid argon environment, respectively. The linear combination of both environmental damage contributions yields satisfactory results over the whole temperature range (curve C). The consideration of environmental effects on fatigue life in TMF is more complicated and demands additional assumptions. Hydrogen embrittlement was assumed to be negligible in the case of IP TMF as stresses are mostly compressive in the low-temperature part of the cycle. Consequently, oxidation was the only environmental effect considered for IP-TMF. By contrast, both environmental degradation mechanisms were accounted for to predict $N_f$ of OP-TMF tests. Oxygen uptake was assumed to be not affected by the sign of the stress. Since high tensile stresses coincide with low temperature in OP-TMF, hydrogen embrittlement must be expected due to the reaction of the alloy with water vapor. Figure 12 compares the experimentally observed TMF lives of IP and OP tests at two values of the plastic strain amplitude with the results of the prediction calculation. As can be seen, all data points lie within a ±2 scatter band.

Fig. 11. Combination (C) of the effect of water (B) and oxygen (A) reducing fatigue life of IMI 834 in air as compared to vacuum [8].

Fig. 12. Accurate TMF life prediction based on the consideration of environmental effects for the titanium alloy IMI 834 [8].
Conclusions

From the results presented as examples to illustrate the variety of behavioural patterns of metallic structural materials under isothermal and non-isothermal conditions, the conclusion can be drawn that the following prerequisites have to be fulfilled, if TMF life shall be predicted:

- The mechanisms relevant for isothermal fatigue must be understood.
- The specifics of TMF must be known and taken into account.
- The material considered must show sufficient cyclic plasticity.
- The method used for TMF life assessment must be selected on the basis of the relevant damage mechanism.

References