Thermal-Mechanical Fatigue of Nickel Base Superalloys – Modelling versus Experiment

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Abstract. The thermal mechanical fatigue behaviour of three different generations of monocrystalline Nickel based Superalloys is compared. Additionally, the material response under non-stationary thermal and mechanical (TMF) loading is modelled on the basis of the threshold stress concept using isothermal creep data. Compensating the applied stresses in terms of a temperature and stress dependent hardening contribution of the second phase particles only a reduced effective stress is active for viscoplastic deformation. Thus, complex deformation behaviour of highly precipitation hardened superalloys can be directly described by the mechanical behaviour of the pure (i.e. particle-free) matrix material. The comparison of the calculated TMF hysteresis loops in terms of a threshold stress to the measured behaviour exhibits excellent accuracy.

Introduction

The efficiency of gas turbines is strongly correlated with the gas in-let temperature. Therefore, improvements in efficiency are consequently combined with significant increases in thermal and mechanical loading of these components. For increasing the high temperature strength of these Superalloys the Rhenium alloying content was steadily increased [1]. With respect to the dramatic prize increase for Rhenium latest efforts focus on the reduction of the Rhenium content by maintaining the high temperature strength [2-4]. The latest result of this development is a Rhenium-free monocrystalline Nickel based Superalloy whose chemical composition was entirely designed by computer modelling. [5,6]. While in the past turbine blades were mainly designed in terms of creep strength capability, today it is common practice to consider start and shut down cycles which result in thermal mechanical fatigue (TMF) damage. This superposition of mechanical and thermal fatigue is regarded to be the main factor which influences life times of turbine blades [7-9].

Experimental

Three monocrystalline Nickel based Superalloys each representing a typical generation are characterized concerning their thermal-mechanical fatigue behavior under out of phase conditions (OP). In detail, CMSX-6, 1st generation and Rhenium free, Reed-1.6, 3rd generation, Rhenium containing and Astra-3OptW, latest generation and Rhenium-free are analyzed in terms of their TMF behaviour. The temperature range was 400 – 980°C at a heating /cooling rate of 10K/sec. Applied mechanical strain amplitudes were 6.0 10^{-3} in all cases. For analyzing stress relaxation effects a hold time of 60 sec was additionally applied under maximum compression and maximum temperature. In this case the mechanical strain amplitude was 5.0 10^{-3}.
In a second step this thermal-mechanical deformation is modelled on the basis of isothermal creep data in terms of the threshold stress concept. This model immplies that viscoplastic deformation at elevated temperatures is dominated by creep effects and can be descried by a modified Norton equation [10] which is supplemented by a threshold stress. Introducing this parameter the creep behavior of complex multiphase alloys can be referred to the creep behavior of the pure matrix material [11].

Results and Discussion

Thermal mechanical fatigue
The resistance against thermal mechanical fatigue decreases in the following row: Astra-3OptW - Reed-1.6 - CMSX-6. Further the integration of a hold time at maximum temperature and maximum compression (out of phase) reduces the lifetime significantly. The reason is that a hold time causes an important increase of the time dependent plastic deformation which leads to a decrease of the life time because of the damaging effect of plastic deformation (time dependent and independent). The damaging effect of a hold time is bigger than the one due to a higher mechanical loading by a higher mechanical strain amplitude. Besides, a strong influence of the crystallographic orientation on the deformation behaviour and life time regarding the different orientations of the specimens of Reed-1.6 is identified. This confirms the results of creep [12] and TMF-tests [13] of alloys in different crystallographic directions. The formation of a mean stress which is expected due to TMF with the out of phase relationship between mechanical strain and temperature is in accord with the temperature. The formation of a mean stress which is expected due to TMF with the out of phase relationship between mechanical strain and temperature is in accord with the temperature dependence of the yield stress and the Young´s modulus. In addition the failure of the specimen is fast and abrupt.

Modelling of the Creep Behaviour

It has been found that the creep behaviour of two-phase superalloys can be put down by the threshold stress concept to the one of single-phase matrix alloys. So the threshold stress concept is suitable for describing the creep deformation of two-phase materials. The values of the single-phase materials for the stress exponent and the activation energy can be used. Thus you avoid material values which are hard to justify physically for these material parameters. A further advantage is that these parameters are generally known for single phase materials.

It can be observed that CMSX-6 exhibits the least resistance against creep deformation. The second phase makes a more significant contribution to the high temperature strength of this alloy in comparison to the second phases of Reed-1.6 und Astra-3OptW. The superiority in high temperature of strength of these alloys can be deduced to the solid solution hardening for a considerable part. Tungsten and Rhenium (only in Reed-1.6) act as solid solution hardener. Plotting the creep data according to Langeborg-Bergmann [11] results in an efficient possibility for the identification of the stress and temperature dependency of the threshold stress.

Modelling of the Thermal Mechanical Fatigue Behaviour

The simulation of the deformation behaviour works excellently by the superposition of Hooke´s law, the Ramberg-Osgood relationship and threshold stress concept. To do so, the identification of the temperature dependence of the material parameter is necessary. The temperature dependence of the Young´s modulus can be found by the so called pretest which is needed for TMF-tests. The Ramberg-Osgood-parameters are assumed to be constant in contrast to a suggestion by [108] which results in a lower number of material parameters what represents a major advantage of the applied model. The central assumption that time-dependent plastic deformation of single crystal Nickel based Superalloys – caused from TMF-loading – can be described by a modified Norton´s law, is verified. Hence, it can be confirmed that the time-dependent deformation due to TMF-loading is caused by creep processes. The material parameters which are used for the simulation of the deformation behaviour due to thermal mechanical loading depend on the crystallographic orientation.

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