International Journal of Fatigue 92 (2016) 262–271

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

# Small-scale specimen testing for fatigue life assessment of service-exposed industrial gas turbine blades

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ARTICLE INFO

*Article history:*
Received 19 May 2016
Received in revised form 13 July 2016
Accepted 15 July 2016
Available online 19 July 2016

*Keywords:*
Nickel-base superalloy
Gas turbine blade
Small-scale specimen
High temperature fatigue
Microstructural degradation

ABSTRACT

Service-exposed industrial gas turbine blades made from conventionally cast nickel-base superalloy IN738 were investigated in order to study the effect of service-induced microstructural changes on the tensile and cyclic material properties. Optical microscopy and scanning electron microscopy were used for the microstructural characterization of the gas turbine blades. The microstructural examinations showed a degraded microstructure in the airfoil section, such as $\gamma'$ coarsening, MC carbide decomposition as well as $M_{23}C_6$ carbide formation. Uniaxial tensile and isothermal low cycle fatigue tests were carried out at 850 °C using small-scale specimens manufactured from the blade root and airfoil section. The service-induced microstructural changes in the airfoil section yielded to a reduction of the tensile properties. Furthermore, a lower fatigue life of airfoil specimens compared to the blade root specimens was observed. Based on the determined fatigue data the residual fatigue life of the gas turbine blades was estimated. Finally, the fatigue crack paths were studied by optical microscopy.


## 1. Introduction

Gas turbine blades are exposed to high temperatures and stresses during service. For this reason, gas turbine blades are made from $\gamma'$ strengthened nickel-base superalloys, which provide excellent high temperature properties. However, several studies of nickel-base superalloys have shown various microstructural changes within the alloy due to thermally induced processes depending on exposure temperature and time [1–6]. Commonly, a coarsening and coalescence of the $\gamma'$ precipitates, an undesirable formation of continuous secondary $M_{23}C_6$ carbide films along grain boundaries and the undesirable embrittling by topologically closed-packed (TCP) phases were observed. Furthermore, an interaction with a mechanical loading causes typically rafting structures in nickel-base superalloys [1,7,8]. Mostly, such instabilities in the microstructure lead to a degradation of material strength and thus have a detrimental effect on the component properties and limit their service life [9–14].

Usually, gas turbine blades are retired from operation after a defined operational period or based on a lifetime counter, whereby in several cases no or only a slight damage is visible. Due to the very high replacement costs of the first stage gas turbine blades, a lot effort is being made to extend the service life of these components beyond the original design life [15–17]. To ensure a further safe operation of the gas turbine components, a realistic estimation of the remaining service life is required, wherefore information about the current mechanical material properties are necessary. A possible method to determine the material properties of service-exposed components is the small-scale specimen test technology, which offers the advantage to investigate specimens directly taken from these components. A successful application of this testing method for residual life assessment of service-exposed gas turbine blades is reported in [11,12,16–19]. Today, the importance of the effects of microstructural changes in service-exposed gas turbine blades and their effect on the tensile properties, creep and stress rupture behavior has been recognized by many researches. However, a lack of information is available on the effect of service-induced microstructural changes on the isothermal low cycle fatigue behavior.

The aim of the present investigation was to study microstructural changes in service-exposed gas turbine blades and their effect on the tensile properties and isothermal low cycle fatigue behavior at 850 °C using small-scale specimen testing. The microstructure of the gas turbine blades was characterized by metallographic examinations. Furthermore, the residual fatigue life of the service-exposed gas turbine blades was estimated based on determined

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http://dx.doi.org/10.1016/j.ijfatigue.2016.07.014
0142-1123/

**Nomenclature**

| | | | |
|---|---|---|---|
| EDM | electrical discharge machining | $\sigma_m$ | mean stress |
| EDX | energy dispersive X-ray spectroscopy | $A_0$ | specimen cross-sectional area |
| HRC | Rockwell's hardness | $A_f$ | elongation at fracture |
| HV | Vickers hardness | $D$ | actual damage |
| LCF | low cycle fatigue | $E$ | Young's modulus |
| SEM | scanning electron microscopy | $l_0$ | gauge length |
| SHT | standard heat treatment | $N_f$ | number of cycles to failure |
| TCP | topologically closed-packed | $R_m$ | ultimate tensile strength |
| $\dot{\varepsilon}$ | strain rate | $R_{p0.2}$ | 0.2% yield stress |
| $\varepsilon_a$ | mechanical strain amplitude | $R_\varepsilon$ | strain ratio |
| $\sigma_a$ | stress amplitude | | |
| $\Delta\sigma$ | stress range | | |

fatigue data. Finally, crack paths of specimens tested under fatigue loading were characterized by optical microscopy.

## 2. Experimental details

### 2.1. Material

Two first-stage gas turbine blades of a GE-MS6001B industrial gas turbine were investigated. In total this gas turbine had 2.696 operating hours and 878 turn-on and turn-off cycles. The gas turbine was operated under peak load conditions. The two blades, which will be further referenced as Blade 1 and Blade 2, correspond to the original stage 1 bucket design (S1B, 13 cooling holes) and were made from conventionally cast nickel-base superalloy IN738 [20]. The nominal chemical composition of this material is given in Table 1. Details about the applied heat treatment were not available. The gas turbine blades were coated with a Pt-Al diffusion coating, which is suitable to improve the hot oxidation and creep resistance [21].

### 2.2. Metallographic examinations

The microstructure of the service-exposed gas turbine blades was analyzed exemplary in case of Blade 1 by optical microscopy, scanning electron microscopy (SEM) as well as energy-dispersive X-ray spectroscopy (EDX). For optical microscopy the specimens were etched using a chemical solution of 40 ml water ($H_2O$), 10 ml hydrogen chloride (HCl), 10 ml nitric acid ($HNO_3$) and 0.1 g molybdenum oxide ($MoO_3$) for 60 s. Metallographic specimens were cut by wire EDM (electrical discharge machining) process directly from the cooler section of the blade root at Pos. 1 and from the hot section of the airfoil at Pos. 2 (leading edge), Pos. 3 (suction side) and Pos. 4 (pressure side) as indicated in Fig. 1. The microstructural images were determined at each position in the longitudinal section (L) of the gas turbine blade. During service the material temperature of the blade root is comparatively low. Therefore, microstructural changes are not expected. Hence, the microstructure of the blade root can be assumed as the initial material state. The maximum damage and microstructural changes were assumed at one-half of airfoil length due to the occurrence of high thermal and mechanical loadings as reported by Lvova and Norsworthy [11] and Frischmuth et al. [15,16] for comparable gas turbine blades. Furthermore, Vickers hardness measurements with an indenter load of 30 kg were conducted in the blade root at section C-C and at several positions (Pos. 2–5) at one-half of the airfoil length (Fig. 1) in case of Blade 1.

### 2.3. Material testing procedure

Uniaxial tensile and LCF tests were carried out on a small-scale specimen test rig consisting of a spindle driven testing machine (*Inspect Table 10, Hegewald&Peschke, Nossen, Germany*) with a load capacity of 10 kN (Fig. 2a). The cylindrical specimen design with threaded connections was introduced by Tartaglia et al. [22] and was further optimized to avoid buckling under compressive force (Fig. 2b). The parallel test length of the specimen has a diameter of 3 mm. Fits at the specimen ends support the specimen alignment. The axial strain was measured with an axial high temperature extensometer equipped with ceramic rods and a fixed gauge length of 7 mm. To prevent an influence of environmental conditions on strain measurement, the extensometer was placed in a tempered housing. A water-cooled radiant furnace with three separated heating zones and a total electrical power of 6 kW was used to heat the specimens. The specimen temperature was controlled at three positions by spot-welded thermocouples type K (Ni-CrNi) with a diameter of 0.2 mm (Fig. 2c). One thermocouple was attached within the gauge length and two in the transition areas to the clampings. An uniform axial temperature distribution in the gauge length was ensured in accordance with ASTM E606. A premature crack initiation in cause of spot-welded thermocouples was not observed during all tests. In previous work, the author's group [23] has shown that this proposed testing configuration is suitable for tensile and LCF testing of the nickel-base superalloy IN738LC at elevated temperatures. As a result, the small scale specimens' results were in good agreement with data obtained from standardized specimens of the same material batch as well as literature data.

The tensile tests and LCF tests were carried out at 850 °C due to commonly reached service temperatures in real gas turbine blades as well as widely available material data of IN738 in the literature. Small-scale specimens were cut by wire EDM process from the blade root section and due to the observed considerable service-

**Table 1**
Nominal chemical composition of nickel-base superalloy IN738 in wt.% [20].

| | Ni | Cr | Co | Fe | W | Mo | Ti | Al | Nb | C | B | Ta |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| IN738 | Bal. | 16 | 8.3 | 0.2 | 2.6 | 1.75 | 3.4 | 3.4 | 0.9 | 0.1 | 0.001 | 1.75 |