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Multiaxial high-cycle fatigue criteria and life prediction: Application to gas turbine blade

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ABSTRACT

A recent work conducted by the authors (Maktouf and Saï, 2015) demonstrated that the root cause of the premature blade failure was caused by high-cycle fatigue (HCF) mechanism initiated at a localized carbon-rich area inducing grain boundary brittleness. The blade was subject to multiaxial cyclic loadings during its service life and any attempt to assess component fatigue strength leads to the question of choosing an appropriate fatigue design criterion. In this paper several multiaxial fatigue models are applied as post-processing step of the Finite Element Analysis (FEA) output results and the estimated fatigue lifetimes were assessed under different loading conditions. The material fatigue parameters, required as an input to the selected fatigue models were determined through a series of bending and torsion tests on specimens made of aged Inconel 718. A numerical post-processing algorithm was developed for Fatemi-Socie fatigue criterion and included as additional post-computation model in the used computer aided fatigue damage evaluation tool. The authors point out that the majority of the multiaxial fatigue studies available in the literature are conducted mainly for correlating the experimental laboratory results on specimens while they have been used in the frame of this study to investigate their application to an industrial case.

1. Introduction

In a recent work, the authors investigated through mechanical, metallography and chemical analysis an industrial case of premature fatigue failure of gas turbine blade [1]. The root cause was attributed to fatigue cracks initiated near the airfoil leading edge and propagated towards airfoil mid-chord until final tensile overload separation occurred. This blade experienced multiaxial cyclic loadings during its service life and damage was attributed to high-cycle fatigue (HCF) mechanism causing grain boundary brittleness. The latter was found initiated at a localized carbon-rich area considered as metallurgical anomaly region that originated during component fabrication phase.

Furthermore, the recorded high incidence of HCF related failures of gas turbine blades [2,3] under multiaxial loading conditions imposes a requirement for an accurate evaluation of blades' material capability under HCF. The component's geometry under multiaxial stress states should then be evaluated with an adequate multiaxial fatigue model for an accurate component fatigue lifetime estimation. Although several research studies have been conducted in this subject, uncertainties still exist as to which multiaxial fatigue model should be used for a particular material and geometry and under a given loading condition. It should be pointed out that the majority of the multiaxial fatigue studies were conducted for correlating the experimental laboratory results on specimens and that a few studies investigated the application of the developed approaches to an actual design for industrial components. To note also that for this schematic, there is no attempt to assess the damage present in the form of initial material or manufacturing defects nor the evaluation of the propagation life as a fraction of component total life. Main focus is for assessing the HCF failure developed during service operation which requires a relatively large fraction of life to initiation.

As stated above, an initial review of the developed multiaxial fatigue models was conducted. Several comparative and evaluation studies are available in the literature [4–14]. Obviously, the aim of the multiaxial fatigue models is to reduce the complex multiaxial loading into an equivalent uniaxial loading where material data from simple and/or uniaxial laboratory tests could be used in computer aided algorithms combined with the finite element method (FEM) for crack initiation life predictions. To authors' knowledge

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there are no universal categorization of the developed multiaxial fatigue models: Multiaxial fatigue theories have been classified initially into five viewpoints [5]: (i) empirical formulas and modifications of the Coffin-Manson equation, (ii) application of stress or strain invariants, (iii) use of the space averages of stress or strain, (iv) critical plane approaches and (v) use of accumulated material's energy. Chen et al. [13] classified the multiaxial fatigue damage models into three main categories: stress-strain based approach, the energy based approach and the critical plane approach. Liu and Mahadavan [14] assumed that the stress-based approaches could be further divided into four sub-categories: empirical equivalent stress, stress invariants, average stress and critical plane stress.

Based on the reviewed literature and the several developed multiaxial fatigue criteria, authors classify the models into four categories based on the physical quantities used in the theories:

- Stress-based models which are applicable for HCF regime where plastic strains are insignificant.
- Strain-based models applicable for both LCF and HCF regimes. These approaches are purely based on strain quantities and couldn't then consider the non-proportional loadings effect causing material hardening and requiring additional stress response in the formulas.
- The energy concept based on the energy quantities assessing the material fatigue failure. It uses a combination of the plastic strain energy with the plastic deformation in a continuous fatigue accumulation formulas.
- The "shear strain"-stress based criterion which includes a combination of strain and stress values.

Critical plane concepts are then covered by the above categories and are defined by the used critical physical quantities. As an example, Findley et al. [15] defined the plane subject to the largest cycle of shear stress as the critical plane, while Fatemi and Socie [16] defined the critical plane as the plane associated with the maximum shear strain amplitude. For an adequate selection of the applicable multiaxial fatigue model, the component subject to multiaxial stress states should be verified if it is subject to proportional (In-phase) or non-proportional (Out-phase) loading. Proportional loading is characterized by fixed principal axes direction during the loading cycle. While for non-proportional loading, the orientation of the principal normal stress axes continuously change with respect to the loading axes and often produces additional cyclic hardening and shorter fatigue life in opposite to the proportional loading. For our industrial case, the blade is assumed subject to proportional loading (centrifugal and aerodynamic loads) where stress components vary proportionally with time and the principal stress directions remain fixed.

In the frame of this study, four multiaxial fatigue models are then selected, assessed and compared for lifetime estimation of the gas turbine blade: Sines, Crossland, Dang Van and Fatemi-Socie criteria. Computer aided fatigue damage evaluation of the component consisted of two phases: Dynamic stress computation obtained from the Finite Element Model (FEM) simulations and the fatigue life prediction carried out as post-processing step of the Finite Element Analysis (FEA) output results.

This paper starts by determining the material fatigue parameters, required as an input to the selected fatigue models, through a series of bending and torsion tests on specimens. Approximation methods were also used to estimate the remaining parameters required for the Fatemi-Socie model (Section 2). Section 3 details the selected fatigue models and the related material parameters to include in the computer aided fatigue algorithms. Section 4 is devoted to the FEA of the component and the results of post-processing calculations. The last section aims at providing a comparison of the fatigue model calculations and a conservative lifetime estimation of the component.

2. Experiments

2.1. Material, specimens and test procedure

The failed blades were made of UNS N07718 material (Formerly Grade 718) which is a Ni-Cr-Fe-Nb alloy. The chemical composition complying with ASTM B637 requirements is prescribed in Table 1. ASTM B637 Alloy 718 product is available in forged bar, blank, ring, and rolled bar. The material is heat treated by solution and precipitation hardening. The recommended heat treatment as specified in the ASTM standard is solution treatment at a temperature of 924–1010 °C (1700–1850 °F), hold for at least half hour and then cooled down at rate equivalent to air cool or faster. This heat treatment is to be followed by precipitation hardening treatment at a temperature of 718 ± 14 °C (1325 ± 25 °F), hold at temperature for 8 h, cool down to 621 ± 14 °C (1150 ± 25 °F), and hold until total precipitation heat treatment time has reached 18 h then air cooled down to room temperature. Inconel 718 alloy differentiates from other Nickel based super-alloys with the relatively high contents of iron [Fe-19%] and Niobium (or Columbium) [Nb-5%].

The folowing experiments have been conducted on specimens machined from rolled bar of 107 mm diameter. Raw material is solution annealed and age hardened as described above (ASTM B637 requirements):

- Magnification micrograph examination of the raw material microstructure.
- Brinell Hardness Measurements.
- Uniaxial tensile test.
- Fatigue tests on smooth cylindrical specimens: Pure alternated bending ($R = -1$); repeated bending ($R = 0$) and alternated torsion ($R = -1$).

The magnification micrograph examination of the material microstructure was carried out on specimens extracted from three locations in the radial-cross section of the bar: (i) center of the bar, (ii) mid radius region and (iii) outer part. Specimens are prepared in compliance to the NFA-05-150 standard: Final polishing with 1 μm DIAMAT diamond on GOLDPAD polishing pad and etching with Kalling's reagent.

Table 1
Chemical composition of UNS N07718 – ASTM B637.

Element	Composition Limits, %	Product(Check) Analysis Variations, Under min or Over max, of the Specified Limit of Element
	UNS N07718 (Formerly Grade 718)	
Carbon	0.08 max	0.01
Manganese	0.35 max	0.03
Silicon	0.35 max	0.03
Phosphorus	0.015 max	0.005
Chromium	17.0–21.0	0.25
Cobalt	1.0 max	0.03
Molibdenum	2.8–3.3	0.05 under min, 0.10 over max
Columbium (Nb) + tantalum	4.75–5.50	0.15 under min, 0.20 over max
Titanium	0.65–1.15	0.04 under min, 0.05 over max
Aluminium	0.20–0.80	0.05 under min, 0.10 over max
Boron	0.006 max	0.002
Iron	Remainder	...
Copper	0.30 max	0.03
Nickel	50.0–55.0	0.35