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Comparative performance of turbine blades used in power generation: Damage vs. microstructure and superalloy composition selected for the application

H.M. Tawancy [*], Luai M. Al-Hadhrami

Center for Engineering Research, Research Institute, King Fahd University of Petroleum and Minerals, Box 1639, Dhahran 31261, Saudi Arabia

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ABSTRACT

First-stage turbine blades made of different grades of Ni-base superalloys and environmentally protected by the same Cr-modified aluminide coating are examined after exposure to the same service conditions in an electric power plant. Emphasis is placed upon microstructural changes, which can degrade the blade performance. Various electron-optical techniques are used to characterize the microstructures of unused and used blades. Three types of microstructural changes, which can lead to intergranular creep failure, are identified. These changes include: (i) coarsening, agglomeration, and rafting of the strengthening γ'-phase, (ii) formation of γ'-denuded zones alongside grain boundaries, and (iii) precipitation of intermetallic compounds. However, fatigue failure is also observed particularly in cases where higher than normal temperature is encountered. Although the same microstructural changes are found to occur in the blades included in the study, the respective kinetics appear to be influenced by at least two parameters: (i) exact superalloy composition and (ii) actual operating temperature. It is concluded that the life expectancy of blades used in such applications can be realized by appropriate selection of superalloy composition and adherence to design specifications.

1. Introduction

To meet the increasing demand for electric power and simultaneously conserve energy and maintain cleaner environment, designers are always motivated to operate industrial gas turbine engines at higher temperatures to achieve higher efficiency and more power output [1]. However, this goal is limited by the heat resistance of material systems used in the turbine section where the temperature reaches its maximum value during engine operation. Therefore, gas turbine design presents an example of a material-driven technology.

Due to the combination of high stresses and temperature encountered in the turbine section, mechanical strength including tensile, creep, and fatigue is the primary requirement, which is mostly satisfied by the superalloys [2–4]. However, because of the inadequate environmental resistance of bare superalloys, the surface integrity of the blades is maintained by protective coatings such as Cr-modified aluminides, Pt-aluminides, and overlays of the MCrAlY-type (M stands for Ni or Ni + Co) [5–7].

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[*] Corresponding author. Tel.: +966 013 8604317; fax: +966 013 8603996.
E-mail address: tawancy@kfupm.edu.sa (H.M. Tawancy).

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Qualitatively, the microstructural features of Ni-base superalloys prior to service are rather similar [4]. Each alloy consists of a fine dispersion of the strengthening γ'-phase based upon the Ni_3Al composition (ordered cubic $L1_2$ superlattice) in a matrix of γ-phase (Ni-rich solid-solution) with face-centered cubic structure (fcc) containing relatively large carbide particles of the MC-type (M stands for metal such as W, Mo, Ti, Ta or a combination of these depending upon the exact chemical composition of the superalloy). Most of the γ'-phase, which assumes a cubical morphology is made to precipitate by a standard aging heat treatment defined for each alloy. However, additional γ' with finer size and nearly spherical morphology is precipitated during cooling from the aging temperature and therefore, it is commonly referred to as cooling γ' [4]. A distinctive feature of the cubical particles of γ'-phase is that they maintain high coherency with the matrix γ-phase. Therefore, the associated coherency strain provides an important source of strengthening. Additional strengthening is also provided by the cooling γ'-phase particularly at lower temperatures [8].

According to design specifications, the life expectancy of turbine blades used in industrial applications ranges from 35,000 to 100,000 h depending upon the engine type, operating conditions, and material systems selected for the application [7]. Although every effort is made to eliminate or minimize the incidents of unscheduled shutdowns and reduce maintenance costs, various types of damage leading to premature failure can still occur due to the combined effects of high temperatures, mechanical stresses and environmental conditions, e.g., [8–15]. In the meantime, because of the initial high material and processing costs, refurbishing of used blades is a common practice to re-qualify damaged blades for service. Various repair techniques have been devised particularly those based upon advanced welding technology [16–18].

Since the superalloys are complex multi-component alloy systems, their initial microstructures prior to service exist in state of metastable equilibrium. Subsequent exposure at elevated temperatures during service can lead to significant changes in microstructure, which can have detrimental effects on properties. Therefore, there has been an increasing interest in developing heat treatment schedules capable of restoring most of the initial microstructural features and properties [19,20]. It is then important to develop an in-depth understanding of the types of microstructural changes and associated degradation modes under actual service conditions [20]. Toward that objective, the present study has been undertaken to emphasize the important role of detailed microstructural characterization in identifying the various degradation modes of turbine blades exposed to service conditions.

2. Materials and experimental methods

First-stage turbine blades made of Udimet® alloys 520, 720, and 710 are included in the study (®Udimet is a registered trademarks of Special Metals Corporation group of companies). Table 1 shows their nominal chemical compositions as well as the compositions of the respective alloy heats included in the study as measured by inductively coupled plasma atomic-energy spectroscopy. All blades were coated with the same Cr-modified aluminide. The damaged blades were removed from different engines of the same model operating under the same conditions as per the design specifications listed in Table 2. For comparative purposes, samples of unused blades were also included in the study.

To reveal the grain structure of the superalloys, specimens were etched in a solution consisting of 80% hydrochloric acid by volume and 20% by volume of 15 mol% chromic acid. Various techniques used to characterize the microstructure included scanning electron microscopy (SEM) combined with energy dispersive X-ray spectroscopy, X-ray diffraction and analytical electron microscopy operating in the transmission and scanning transmission modes (TEM/STEM) combined with energy dispersive spectroscopy. Specimens for SEM were examined at 20 keV in the as-polished and etched conditions. Whenever applicable, oxidized fracture surfaces were descaled in HCl prior to SEM examination. X-ray diffraction experiments were carried out on polished specimens using Cu Kα radiation. Thin-foils for TEM/STEM were prepared by the jet polishing technique in a solution consisting of 30% nitric acid and 70% methanol by volume. All foils were examined at 200 keV.

Table 1
Chemical compositions in wt.%; nominal (measured).

Element	Udimet 520	Udimet 720**	Udimet 710
Ni	Balance (56.86)	Balance (58.07)	Balance (57.54)
Co	11–14 (13.70)	14.5–15.5 (14.97)	13–17 (15.12)
Cr	18–20 (19.32)	15.5–16.5 (15.10)	16–20 (18.87)
Al	1.8–2.3 (2.08)	2.25–2.75 (2.66)	2–3 (2.74)
Ti	2.9–3.25 (3.12)	4.75–5.25 (4.86)	4–6 (4.79)
Mo	2–4 (3.74)	2.75–3.25 (3.07)	2–4 (3.38)
W	0.8–1.2 (1.18)	1–1.5 (1.23)	1–2 (1.56)
Si	–	–	–
Mn	–	–	–
Fe	–	–	–
Zr	–	0.025–0.05 (0.04)	–
B	0.004–0.01 (ND)	0.01–0.02 (ND)	0.02* (ND)
C	0.02–0.06 (ND)	0.01–0.02 (ND)	0.07* (ND)

ND: not determined.
* Maximum.
** Low-Cr version.