DOI: 10.2478/fas-2023-0002
FATIGUE OF AIRCRAFT STRUCTURES
Volume 2023: Issue 15, pp. 22–27

HIGH-TEMPERATURE FATIGUE TESTING OF TURBINE BLADES

Mateusz Kopec*, Dominik Kukla, Mirosław Wyszkowski,
Zbigniew L. Kowalewski
Institute of Fundamental Technological Research, Polish Academy of Sciences,
5b Pawińskiego Str., 02-106 Warsaw, Poland.

mkopec@ippt.pan.pl

Abstract

This paper evaluates the efficacy of a patented grip for high-temperature fatigue testing by establishing the S-N curve for full-scale nickel-based turbine blades under simulated environmental conditions. Initially, a bending test assessed the stress-displacement characteristics of the component. This was followed by a series of fatigue tests at 950°C, using cyclic bending with force amplitudes from 5.2 kN to 6.6 kN and a constant frequency of 10 Hz. The setup, integrating the grip into a standard testing machine, proved effective for high-temperature tests and successfully determined the service life of full-scale components.

Keywords: fatigue, high temperature, turbine blade, full-scale fatigue test.
Article category: research article

Introduction

The power and efficiency of aircraft engines are primarily influenced by the inlet gas temperature (Barwinska et al. 2023a). Consequently, it is desirable to increase the temperature of the flue gas to the combustion temperature of aviation fuel, approx. 2300°C (Kukla et al. 2021a). However, certain limitations are posed by the strength properties of the alloys from which the blades are produced. Nickel superalloys are typically used under such conditions in view of their superior properties including corrosion and creep resistance (Kukla et al. 2021b). The additional application of thermal barrier coatings (TBC) on such nickel-based superalloys allows the effective service temperature to be increased to 1300°C, while keeping the blade attachment temperature below 300°C (Barwinska et al. 2023b). Moreover, the durability of engine turbine blades is affected by the aggressive environments they operate in (Ziaei-Asl and Ramezanlou, 2019). Factors such as fuel combustion products (e.g., Na_2SO_4, NaCl, V_2O_5), oxidation, hot corrosion, erosion, and foreign object damage can significantly diminish their service life (Kukla et al. 2020). High-temperature fatigue testing of materials operating in aggressive environments is vital for assessing the service life of high-strength materials used in aircraft engines (Bhaumik et al. 2008). However, strength characteristics are typically determined based on standardised specimens, which fail to fully represent the complex behaviour of turbine components. Moreover, this approach yields only limited data on component behaviour, as it predominantly reveals only material-related features. It is crucial to test critical engine components under conditions that accurately reflect their actual ones (Liu et al. 2021).

To address industry needs, several novel methods have been developed for addressing the fatigue response of full-scale turbine blades. For instance, the setup proposed by Beghini et al. (2017) successfully reproduced the stress–strain response from the fillet region between the trailing edge and platform of cooled turbine blades. Wang et al. (2019), in turn, introduced a complex thermomechanical fatigue (TMF) test rig with loading, heating, cooling, and control subsystems. Although some modifications have been made to improve the reliability of turbine testing in the laboratory scale, the current knowledge on turbine blade behaviour under high-temperature fatigue remains limited. Puspitasari et al. (2021) reported that turbine blade damage usually occurs due to multiple phenomena and factors, including fatigue, creep, oxidation, coating degradation, corrosion, erosion, and surface degradation at high temperatures. Therefore, there is a continual need to develop new experimental setups that can precisely characterize the behaviour of full-scale components operating under high-temperature conditions.

This paper proposes a new design of the grip for high-temperature fatigue testing. Its effectiveness was tested by determining the S-N curve for full-scale nickel-based turbine blades operating under their environmentally simulated conditions.

Materials and methods

High-temperature fatigue tests were conducted using the MTS 810 and a patented new testing stand (Kowalewski et al. 2023). This stand was placed into the grips of a conventional servo-hydraulic testing machine (Fig. 1a). Once the turbine blade was secured to the stand (Fig. 1b), a heating coil connected with an induction heater was used to raise the temperature to 950°C during testing (Fig. 1c). Force control mode was employed to apply the load to the turbine blade surface, using an Inconel round-ended bar. The range of fatigue loads was determined from the force/displacement curve obtained from a bending test executed at 950°C. The fatigue tests were performed at a frequency of 10 Hz, with load amplitudes ranging from 5.2 kN to 6.6 kN. Temperature stability was continually monitored using a bicolour infrared pyrometer, as shown in Figure 3c. Fatigue testing commenced 1 h after the turbine blade reached the testing temperature – this heating duration was chosen to minimize the impact of thermal expansion on the material's behaviour during testing. The results were recorded as hysteresis loops for selected loading cycles, continuing until the turbine blade fractured (Fig. 1d). The testing stand, machined from heat-resistant, high-rigidity Inconel alloy, was designed to facilitate precise, high-temperature fatigue testing, without potential bending effects.

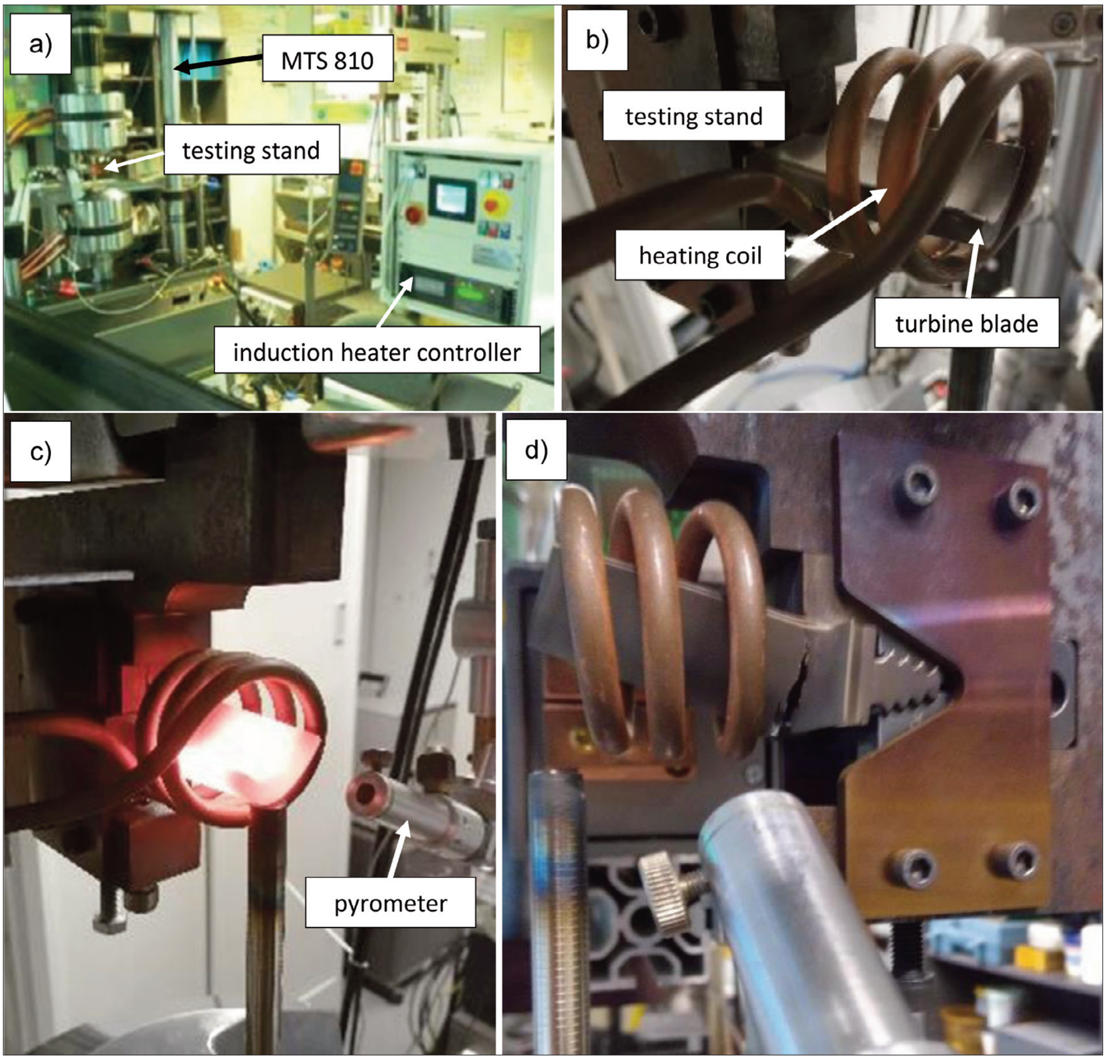

Figure 1. General view of the experimental setup (a); a view of the turbine blade attached to the grip, positioned inside the heating coil (b); high-temperature fatigue testing of a turbine blade at 950°C (c); the fractured turbine blade after testing (d).

Results and discussion

Initially, a uniaxial bending test was performed to determine the force required to fracture the turbine blade attached to the testing grip (Fig. 2a). The resulting reference force, determined to be 6.8 kN at a displacement of 4 mm, informed the selection of the bending force amplitude for the subsequent fatigue tests. Six independent fatigue tests were performed in the force range of 5.2 kN to 6.6 kN, leading to derivation of the S-N characteristics (Fig. 2b). High-frequency data recording during the tests facilitated the collection of detailed information for hysteresis loop analysis (Fig. 2c-d).

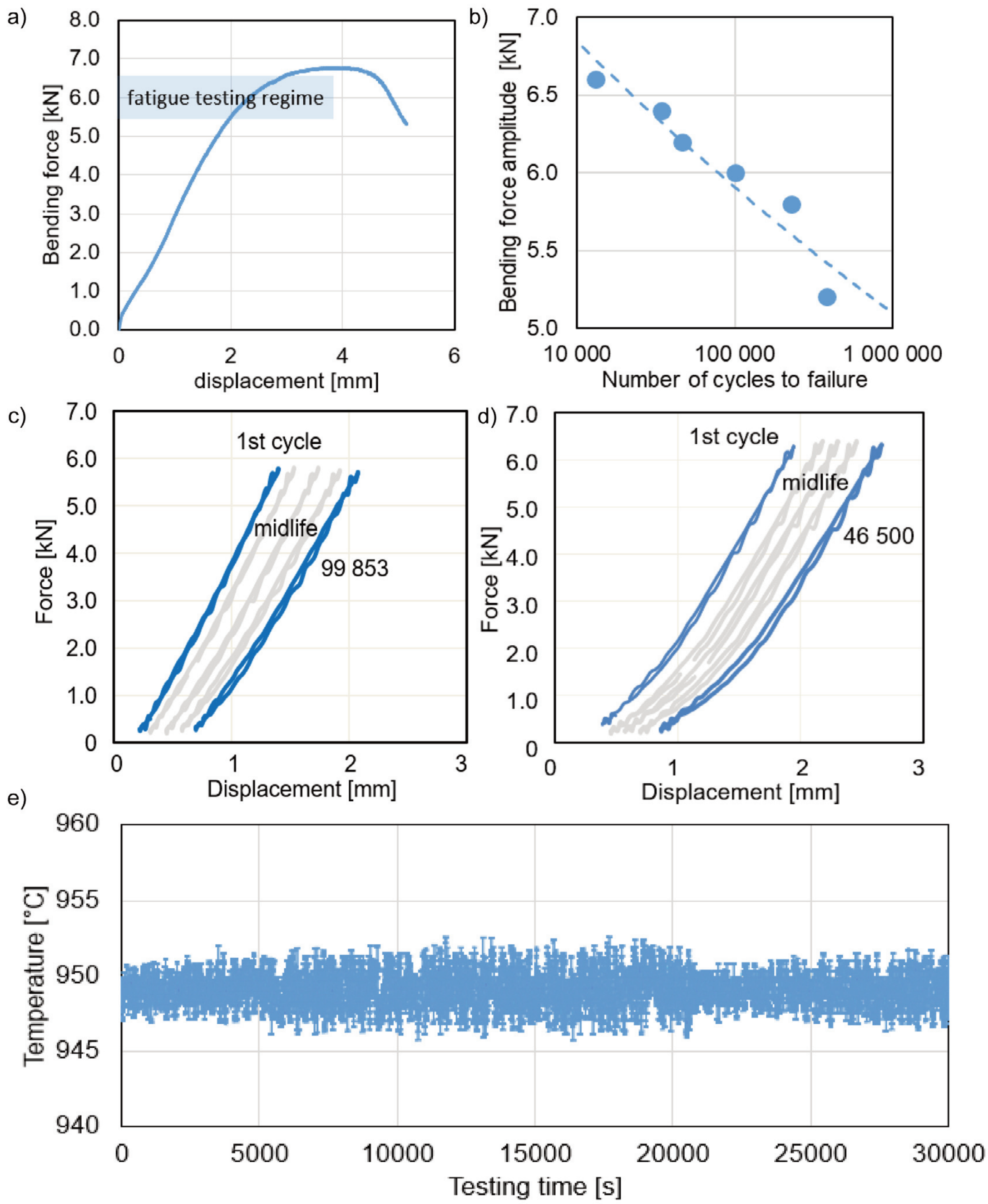

Figure 2. Bending characteristic of the exemplary turbine blade at 950°C (a); S-N curve for turbine blades subjected to fatigue at 950°C (b); selected hysteresis loops obtained at forces of 5.8 kN (c) and 6.2 kN (d); temperature recordings during testing (e).

The behaviour of the turbine blades varied distinctly with different force amplitudes applied. A nearly elastic response was observed at force amplitude of 5.8 kN (Fig. 2c), whereas a notable distortion of the hysteresis loop was observed at 6.2 kN (Fig. 2d). This loop shape variation was presumably caused by the higher force applied, likely inducing plastic deformation of the turbine blade during the subsequent loading cycles. Note that regardless of the force amplitude value applied, the behaviour of the full-scale turbine blade was successfully monitored using the force-displacement relation. Furthermore, the heating system integrated into the testing stand enabled the high temperature to be maintained during the experiment within the reasonable variance of ±3°C (Fig. 2e). As the proposed testing stand can be fixed to any conventional testing machine, the development of fatigue damage in turbine blades subjected to cyclic loading at high temperature can be also monitored (Fig. 3). High-frequency data collection ensured that each hysteresis loop could be captured, allowing for analysis of loop evolution across successive loading cycles.

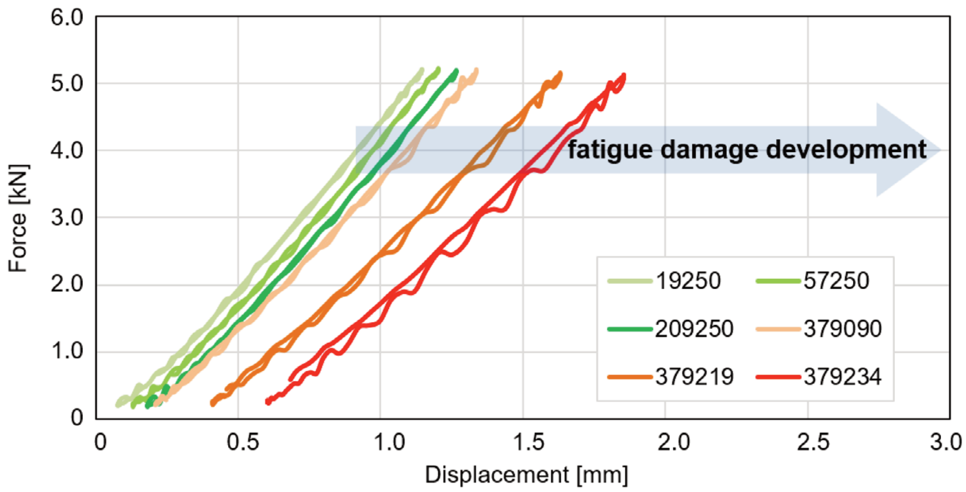

Figure 3. Development of fatigue damage in turbine blades subjected to fatigue at 950°C with force amplitude of 5.2 kN.

Conclusions

The proposed experimental setup for high-temperature testing of full-scale turbine blades under cyclic loading proved effective during fatigue tests executed at 950°C. The design of the new testing stand enabled precise determination of both the S-N characteristic and the evolution of hysteresis loops throughout the testing programme. Furthermore, the development of fatigue damage in the turbine blades was effectively monitored based on the data recorded during tests, further confirming the setup's efficiency and precision. The outcomes highlight the setup's capacity to provide detailed insights into turbine blade behaviour under high-temperature, high-stress conditions.

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