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Thermomechanical fatigue failure investigation on a single crystal nickel superalloy turbine blade

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ABSTRACT

A thermomechanical fatigue (TMF) test rig was developed consisting of the loading, heating, synchronizing, cooling and monitoring systems. Moreover, the specimen was particularly designed to provide adequate load-bearing capability at the blade tip in order to simulate the actual turbine blade loads in laboratory. TMF test on a single crystal nickel superalloy turbine blade was conducted. Then the specimen was segmented in a novel way to preserve the crack surface to investigate the TMF mechanism of the turbine blade. Visual examination together with the metallographic analysis indicated that the most severe TMF damage occurred at the pin-fin fillet on the suction side near the trailing edge. Furthermore, finite element simulation results were compared to the experiment, in which a viscoplastic constitutive model was employed.

1. Introduction

Single crystal nickel superalloys are widely used to manufacture turbine blades and vanes in gas turbine engines for their superior high temperature performance [1]. Turbine blades operating in engines are subjected to simultaneously occurring thermal loads caused by the high temperature gas, and mechanical loads induced by the centrifugal force [2]. Generally, failure due to the contribution of both thermal and mechanical loading is termed thermomechanical fatigue (TMF), which is a major life-limiting factor for gas turbine blades [3–5]. Therefore the investigation on the TMF failure is of special interest in the gas turbine industry.

Over a period of years, experiments on standard specimens, such as round bars, are extensively conducted to investigate the material's deformation behavior and damage mechanisms under TMF loading [6–8]. Through these fruitful experiments, a wide variety of models involving constitutive equations for single crystal superalloy and TMF damage models has been established. These experiments facilitated the understanding of the TMF damage mechanism of the single crystal nickel superalloy material instead of the turbine blade, which laid a foundation for lifetime prediction. However, a sophisticated cooling scheme including intricately designed channels, film-cooling holes and pin-fins is widely used in modern advanced turbine blades in order to achieve the required lifetime, which results in extremely non-uniform stress/temperature fields under the service condition [4]. In addition, actual single crystal nickel based turbine blades are manufactured by investment casting [1], which is remarkably different from standard specimens fabricated by machining methods like turning, milling, grinding and polishing. These differences may cause discrepancies between their mechanical performance and life distribution [9].

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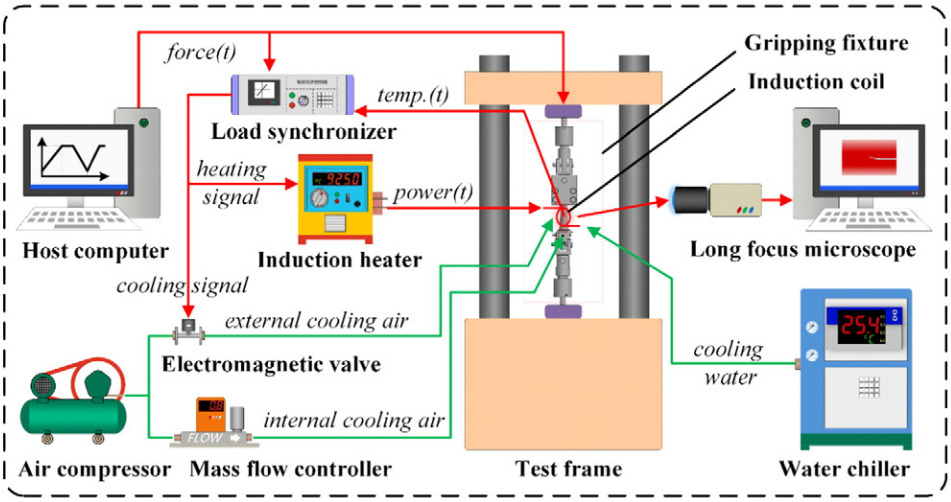

Fig. 1. The turbine blade TMF test system.

It is known that performing aeroengine test under service condition to investigate turbine blades' failure is nearly impossible due to extremely high cost and difficulties in measuring turbine blades' temperature and stress fields. Consequently, the development of TMF experimental methods for actual turbine blades in lab is of great importance [10]. More recently, lots of experiments on the blade-like specimens and full scale blades have been carried out to meet the industrial requirements [5,10–14]. Especially the experiments on actual turbine blades help to investigate their failure mechanism in an affordable way. Additionally, experimental results can modify the developed models based on the standard specimen experimental data.

In this regard, the objective of this paper is to provide an effective method to investigate the turbine blade's TMF failure. A TMF test rig on actual turbine blades was constructed. Then a particularly designed specimen was tested under the TMF loading. The tested specimen was preliminarily inspected by an analytic scanning electron microscopy (SEM), and then segmented into metallographic samples through a new method to observe the crack surface directly. Visual examination and SEM inspection were performed on the samples to identify the TMF mechanism of the turbine blade by detailed microstructural characterization referred to [15,16]. In addition, finite element simulation based on a viscoplastic constitutive model was also conducted to validate the location where most sever TMF damage manifested.

2. Experimental details

2.1. Experimental set-up

Fig. 1 illustrated the TMF experiment system for the turbine blade, which consisted of a servo-hydraulic testing machine, a set of gripping fixture, a high frequency induction heater, an induction coil, a load synchronizer, a long-focus microscope, and the air/

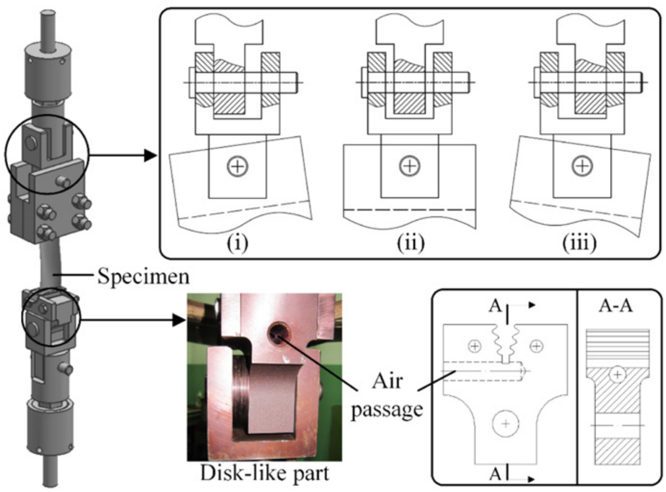

Fig. 2. Gripping fixture schematic diagram.