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The influence of temperature transients on the lifetime of modern high-chromium rotor steel under service-type loading

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ABSTRACT

Nowadays, fossil power plants are increasingly required to start up and shut down frequently due to the flexibility of electrical power demand. Thermomechanical fatigue (TMF) induced by temperature transients with superimposed creep on the heated surfaces of components leads to a significant reduction of lifetime. In this paper, the influence of temperature transients on the crack initiation behavior of high-chromium rotor steel of the type X12CrMoWVNbN10-1-1 was studied by performing uniaxial and biaxial service-type TMF experiments. The experiments represent a range of steam turbine cycles with a maximum temperature of 600° C. A significant lifetime reduction was observed on TMF loading compared to isothermal loading under the same mechanical strain cycle. Metallographic examinations have been employed to characterize the associated thermal fatigue damage mechanisms for comparison of the damage evolution under isothermal loading. In particular, the evolution of damage was investigated by systematic metallographic examinations to study the temperature influence on the crack initiation behavior.

1. Introduction

The lifetime of steam turbine components of fossil power plants is usually influenced by variable loading conditions. These components are subjected to start-up phases, (quasi-) constant load phases and shut-down phases with respect to cold start (CS), warm start (WS) and hot start (HS) [1,2]. Temperature transients, constant or variable pressure in pressurized systems and constant or variable speed of turbine rotors produce a large variety of combined static and variable loading conditions. The pressure loading and centrifugal loading on rotors lead to quasi-static (primary) stress (Fig. 1) [1,2]. In addition, temperature transients cause strain cycling with variable thermal (secondary) stresses on the heated surfaces of turbine components. As a consequence, creep fatigue is considered to be the critical loading condition for high-temperature components.

Crack initiation behavior of steam turbine components under creep fatigue loading is traditionally examined under isothermal conditions at maximal operating temperature [1–5]. With the requirements of frequent start-up und shut-down processes of power plants due to the flexibility of electrical power demand, in addition to creep and creep fatigue endurance, thermal mechanical fatigue cracking behavior has increasingly become an area of great interest (e.g. [6–14]). These investigations usually describe TMF life behavior independently of microstructural damage mechanisms. For service relevant biaxial loading, the investigations are limited to isothermal conditions [13]. The influence of temperature load range on lifetime was examined in conventional 1%CrMoV steel [8,14]. However, a direct comparison of damage evolution is absent. New models take into consideration an increased crack density and the effect of grain size on crack initiation in fatigue and creep–fatigue lifetimes [9].

The main focus of this research explores the direct comparison of crack initiation and propagation behavior under TMF and isothermal loading conditions on modern 10%Cr steel of the type X12CrMoWVNbN10-1-1. Series of pair experiments consisting of TMF and isothermal loading are carried out under an identical mechanical strain cycle sequence. TMF experiments are performed under a service-type temperature profile and isothermal tests are performed at a maximal operating temperature of 600 °C on cylindrical and cruciform specimens. Furthermore, the evolution of damage is characterized by systematic metallographic examinations.

2. Experimental

2.1. Material

The modern ferritic–martensitic heat-resistant steel of the type X12CrMoWVNbN10-1-1 is proposed to be suitable for high

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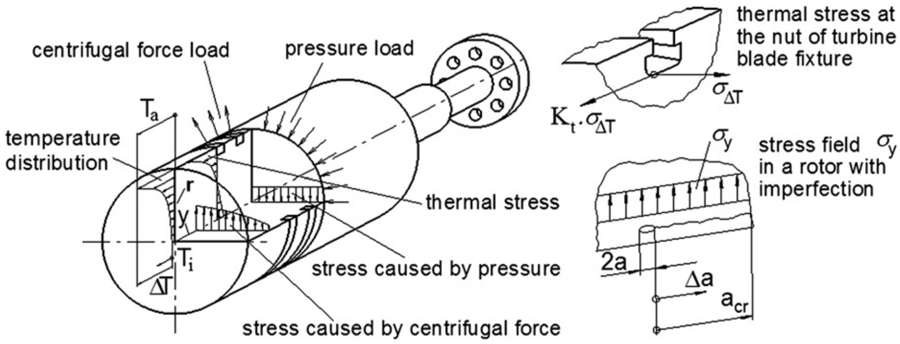

Fig. 1. Load conditions at a turbine rotor showing primary loading and secondary loading.

Table 1
Chemical composition (weight %) and heat treatment of X12CrMoWVNbN10-1-1.

	C	Cr	Mo	W	Ni	V	Nb	N	Mn	Si	P
X12CrMoWVNbN10-1-1	0.12	10.7	1,04	1.04	0.76	0.16	0.05	0.06	0.42	0.1	0.007
Manufacturing	Segment of a rotor diameter 400 mm x 6500 mm, weight 6000 kg, forged										
Heat treatment	Austenitization 1050 °C 7 h/oil + 570 °C 10.25 h/air + 690 °C 10 h/air										

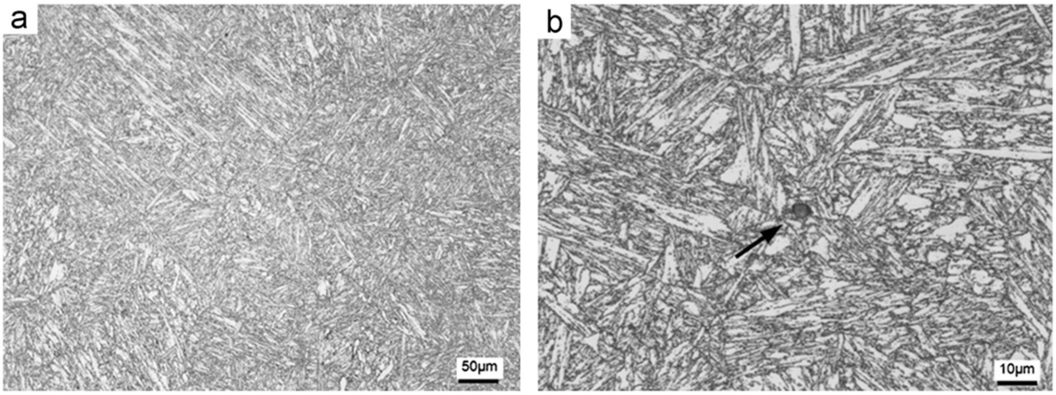

Fig. 2. Initial state of the steel X12CrMoWVNbN10-1-1 after heat treatment with 500 × magnification (a) and 1000 × magnification (b). Non-metallic oxide inclusions (arrow).

temperature applications up to 600 °C/300 bar. This steel was developed in European COST Material Programs [15]. Chemical composition and heat treatment of the material are listed in Table 1. Results of the basic material characterization are given in [15]. Microstructure of the steel after the heat treatment consists of tempered martensite with some amounts of ferrite with homogeneous precipitated carbides. A small amount of very fine globular nonmetallic inclusions of type Al_2O_3 is homogenously distributed in the material (Fig. 2). A homogeneous microstructure with an average grain size of ASTM No. 5 has been reported in [15].

All specimens were manufactured from the same heat. Since the maximal thermal damage occurs on the heated surface of a rotor, the specimens were taken from locations close to the periphery of production forging with a longitudinal orientation with respect to the axis of the rotor.

2.2. Experimental details

Uniaxial experiments were conducted with a cylindrical specimen featuring a parallel length of 16 mm and diameter of 7.9 mm. They were performed on a servo-hydraulic testing machine with a maximum force capacity of ±100 kN and an MTS controller. Total strain control was achieved using a side contact extensometer with an initial gauge length of 15 mm.

Biaxial experiments were performed on a biaxial cruciform testing system developed in cooperation by IfW Darmstadt and INSTRON Ltd. [16]. The cruciform specimen was designed by finite element analysis in order to achieve a uniform stress distribution in the gauge section. A cruciform specimen consists of a circular test zone, a stiff ring surrounding the test zone and four specimen arms. The test zone has a diameter of 15 mm and a thickness of 2 mm (Fig. 3). Total strain control was performed by the usage of a cruciform side contact biaxial extensometer with an initial gauge length of 13 mm. Details of the experimental setup are given in [16].

The service-type cycle is characterized by 4 ramps and 4 hold phases (Fig. 4a). The compressive ramp before hold phase 1 represents the mechanical strain induced by the radial temperature gradients in the turbine rotor at the beginning of the start-up phase. Compressive strain hold phase 1 simulates a steady state of temperature gradients between the surface and inside of the rotor during start-up. Subsequently, the compressive ramp after hold phase 1 describes the final start-up phase when radial temperature gradients disappear. Analogously, the two tensile ramps and hold phase 3 simulate the shut-down process. The zero strain hold phases 2 and 4 approximate temperature quasi-balance