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Thermomechanical fatigue behavior of an air plasma sprayed thermal barrier coating system

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ABSTRACT

Failure behavior of an air plasma sprayed thermal barrier coating (TBC) system was investigated under in-phase (IP) and out-of-phase (OP) thermomechanical fatigue (TMF) tests. All the TMF tests were performed in the temperature range of 450–850 °C with a given period of 300 s under mechanical strain control. Both the bond coat NiCrAlY and the top coat 7%Y_2O_3–ZrO_2 were fabricated by air plasma spraying (APS). Results revealed that the IP TMF lifetime was longer than that of the OP TMF under the same mechanical strain amplitude. Morphology observations of the failed specimens showed that the coating cracking and spallation processes were different in the two phase conditions.

1. Introduction

Thermal barrier coating (TBC) systems have been widely used to hot section parts of gas turbine engines to provide thermal protection to metallic components [1–3]. They offer potential for lowering the temperature of the metal substrate and thus produce an increase in power efficiency and a decrease in greenhouse gas emission. A typical TBC system consists of a superalloy substrate, a bond coat and a ceramic top coat, usually ZrO_2 stabilized with 6–8 wt% Y_2O_3 [4].

In service, hot section components experience severe cyclic temperature gradients and mechanical loads. As a consequence, thermomechanical fatigue (TMF), which provides a closer simulation of the actual strain-temperature cycle in an engine environment, is a major life limiting factor for gas turbine blades [5]. Therefore, TMF tests are useful for evaluating the service lifetime of a TBC system, for identifying the damage mechanism, and for a life modeling approach. However, only a few publications are available in the open literature with regard to TMF tests of TBC systems [6–15]. The main reasons for the limited number of publications are: (1) the difficulty of obtaining sufficiently powerful heating and cooling technique associated with the poor heat absorption and conductivity of the ZrO_2 top coat in the TBC system [9,11], and (2) establishing a service-like temperature gradient across the thickness of the TBC system.

Different heating equipments have been adopted in TMF tests for TBC systems, such as radiation furnaces [6,12], direct or indirect induction heating [8–11], and lamp furnaces [7,13–15]. The first published paper reported the results for a silicon carbide igniter furnace for heating a TBC system, which produced a temperature gradient around 50 °C during transient heating and less than 20 °C during a high temperature dwell [6]. Then induction heating was used to perform a TMF test on a TBC system and obtained an inverse temperature gradient across the coating that was contrary to the in-service situation [8]. Later, an indirect induction heating method was developed and produced a temperature difference of 50 °C between the top coat and substrate during the high temperature hold, but the heat transfer susceptor was hard to select and the test period was long [9–11]. A heating system closer to the ideal was the lamp furnace, which could heat specimens up to 1000 °C in a few seconds [13–15] and obtain a temperature gradient of about 170 °C [14,15]. Among these studies, it was found that the relationship of the lifetime for TBC systems between in-phase (IP) TMF and out-of-phase (OP) TMF is variable. Wright [6] found that the OP TMF lifetime of the TBC system was longer than the IP TMF one, whereas Baufeld et al.'s experiments [10] revealed that the IP TMF lifetime was longer. The cracking and failure mechanisms of TBC systems reported by different authors were also variable. Although TBC systems typically fail by coating delamination or spallation under TMF conditions [6,8–11,13,15], the crack initiation sites are different. Cracks may develop from the uncoated inner surface [10,11], the bond coat [8,10], or the interface between the bond coat and the top coat [9]. As a result, it is difficult to understand the fracture behavior of TBC systems under service conditions and to predict the lifetime of the components.

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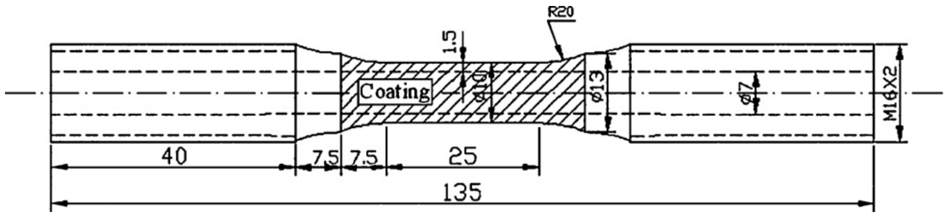

Fig. 1. Dimensions of TBC specimens for thermomechanical fatigue tests.

The bond coat, usually *M*CrAlY overlay coating (where *M* is Ni, Co, or a combination of these elements), is the most crucial component of the TBC system [16] that can be produced by thermal spraying, sputtering or evaporation; however, for practical applications, thermally sprayed coatings are normally preferred [17]. Among thermal spraying techniques, APS and high velocity oxygen fuel (HVOF) can be conducted at atmospheric pressure, therefore their equipment investment and production costs are low compared with vacuum plasma spraying (VPS). Meanwhile, APS shows a considerably better efficiency than other methods [18]. Thus it is attractive to spray the bond coat by APS.

The aim of this paper is to present experimental results concerning TMF lifetime and failure behavior of a TBC system consisting of a Ni-based superalloy substrate, a NiCrA1Y bond coat and a Y_2O_3–ZrO_2 top coat, both of which were fabricated by APS. The relationship of the lifetime and differences of the cracking behaviors between the IP and OP conditions are discussed.

2. Experimental

The cast Ni-based superalloy M963 was used as a substrate. Its chemical composition (in wt.%) was C 0.15, Cr 8.89, Al 6.00, Ti 2.55, Mo 1.64, W 10.1, Co 10.0, Nb 1.10, Zr 0.03, B 0.03, Ce 0.02, Y 0.01 and Ni balance. Before machining, the specimens were solution-treated at 1210 °C for 4 h followed by air cooling. Cylindrical tube specimens were machined with a total length of 135 mm, an internal diameter of 7 mm and in the gauge length an external diameter of 10 mm as shown in Fig. 1. Before spraying these specimens, all the substrates were grit blasted by alumina powder with 80 mesh grain size distribution. The coating substrate was deposited by APS with a Ni–25Cr–5Al–0.5Y alloy as the bond coat with a normal thickness of 130 μm and 7%Y_2O_3–ZrO_2 as the top coat with 250 μm thickness. The APS setting was METCO 7 M and spray parameters for the bond coat and the top coat are listed in Table 1.

The TMF tests were performed on an MTS810 closed-loop servohydraulic testing machine with computer control. A radiation furnace powered by four cylindrical quartz lamps, each with a maximum power of 2.5 kW, was used for heating. The radiation of the quartz lamps was focused on the specimen by reflection from elliptical mirrors. The outer surface temperature of the specimen, which was controlled by the power output of the lamps, was measured with a thermocouple enlacing the specimen. Cooling was obtained by internally compressed air combined with reducing the power output of the lamps. Axial strain amplitudes were controlled using a self-supporting extensometer that had a gauge length of 23 mm, supported with ceramic rods. A triangle waveform was used for both thermal cycling and mechanical cycling. Two kinds of TMF tests were used: IP where the maximum mechanical strain coincided with the maximum temperature and OP where the maximum mechanical strain was attained at the minimum temperature. TMF tests were carried out in the temperature range of 450–850 °C with a cyclic period of 300 s under mechanical strain control. The mechanical strain amplitudes were varied from 0.35% to 0.5% with a strain ratio of −1. The apparatus yielded a temperature difference of about 90 °C between the top coat and the substrate during dwells at the top coat temperature of 900 °C.

Table 1
Spray parameters for bond coat and top coat.

	Bond coat	Top coat
Spraying distance (mm)	145–150	70–120
Feed rate (g/min)	30–45	35–45
Carrier gas (Ar) pressure (MPa)	0.40–0.55	0.40–0.55
Voltage (V)	40–60	45–65
Current (A)	500–530	500–550

After the TMF tests, the cyclically induced morphologies of all specimens, were recorded by a high accuracy digital camera, and fracture surfaces were investigated using a scanning electron microscope (SEM). Longitudinal sections were cut from the tested specimens and were embedded in an epoxy resin. Then these sections were metallographically prepared and observed by the SEM.

3. Results

3.1. Cyclic deformation and fatigue lifetime

Fig. 2 shows the typical stress–mechanical strain hysteresis loops for IP TMF and OP TMF at a mechanical strain amplitude of 0.45%. It can be seen that the maximum and minimum stress of each hysteresis loop are unsymmetrical. In IP TMF, the value of the maximum stress is lower than that of the minimum one, while it is opposite under OP TMF, and the value of the maximum stress is higher.

The cyclic stress response behavior at a mechanical strain amplitude of 0.45% is shown in Fig. 3, which displays the variation of the maximum stress (σ_{max}) and the minimum stress (σ_{min}) as well as the mean stress (σ_m) with the number of cycles (*N*). In the tensile stress cycles, the maximum stress (σ_{max}) gradually decreases in IP TMF but increases under OP TMF with an increase in *N*. In the compressive stress cycles, the tendency of the minimum stress (σ_{min})

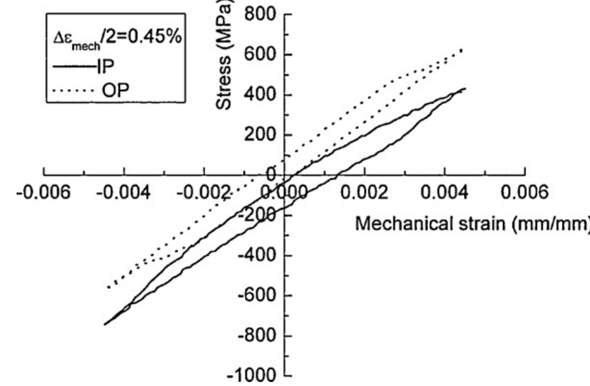

Fig. 2. Middle-life hysteresis loops for IP and OP TMF at $\Delta\varepsilon_{mech}/2 = 0.45\%$.