Rare Metal Materials and Engineering
Volume 46, Issue 12, December 2017
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: Rare Metal Materials and Engineering, 2017, 46(12): 3693-3698.

ARTICLE

Effect of Strain Ranges and Phase Angles on the Thermomechanical Fatigue Properties of Thermal Barrier Coating System

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Abstract: Thermal barrier coatings (TBCs) are the key material of components used in elevated temperature of gas turbines, and their mechanism of delamination and failure under service conditions has been the hot spot of research for a long time. The influences of strain ranges and phase angles on the thermomechanical fatigue (TMF) properties of samples with TBCs were investigated. It is shown that under the same phase angles, the TMF lifetime decreases with the increase of strain ranges. Under the same strain range, the in-phase tests have longer TMF lifetime than out-of-phase tests. In both samples, cracks are initiated in thermally grown oxide (TGO) layer, and then propagate along the bond coat/ceramic top coat, forming the delamination cracks. When the delamination cracks connect with the segmentation cracks initiated in ceramic coat, the TBCs spall. A TMF lifetime model concerning strain ranges and phase angles is established, and an exponential law exists between TMF lifetime and the maximum stress.

Key words: Ni-base superalloy; thermal barrier coatings; thermomechanical fatigue properties; lifetime model

Gas Turbine has been widely utilized in the industry, power generation and aviation fields recently[1]. To achieve a higher working and energy efficiency of gas turbine, the inlet temperature elevates gradually from 900 °C to 1425 °C. This brings about many negative effects at high temperature, such as oxidation, and hot corrosion. Hence the protective thermal barrier coatings (TBCs) get applied by overlaying the superalloy substrate due to their heat-insulation, anti-corrosion performance[2-4].

Generally, a TBC component is a multilayer system consisting of a ceramic top coat (TC), a metallic bond coat (BC) and a superalloy substrate[5,6]. Usually, the TC is about 6~8 wt% Y_2O_3 stabilized ZrO_2 (YSZ) applied either by air plasma spraying (APS) or by electron-beam physical vapor deposition (EB-PVD). The purpose of the BC, typically a *M*CrAlY (*M*=Ni, Co, or NiCo), is dual. It improves the adherence of the TC to the substrate and acts as an oxidation barrier for the substrate. In addition, during the coating process and later in service at high temperatures, a thermally grown oxide (TGO) layer, which mostly consists of stable α-Al_2O_3, develops between the BC and the TC[7].

During service, the gas turbine blades endure high level dynamic mechanical stress as well as rapidly changing temperatures. The thermomechanical fatigue (TMF) is a major lifetime limiting factor, which causes the delamination of the ceramic TC from the BC and the loss of the TBCs[8-11]. This accelerates localized oxidation or might even lead to local melting at high gas temperatures, thus promoting failure of the components. The complex process of TBC degradation[12] is affected by: (1) growth of the TGO and thermal-expansion mismatch strains and stresses at the metal-ceramic interface; (2) temperature gradient across the TBCs and sintering processes in the TBCs, which affect stiffness, thermal conductivity and crack resistance; (3) diffusion of elements from the base material and BC to the interface; (4) cyclic plastic and time dependent deformation, as well as stress relaxation, etc.

The TMF life for TBC systems is influenced by many

Received date: December 11, 2016
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factors, such as sample sizes, strain ranges, phase angles, temperature ranges, heating and cooling rate. Among these factors, 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[13] found that the OP TMF lifetime of the TBC system was longer than the IP TMF one, whereas Baufeld's experiments[14,15] revealed that the IP TMF lifetime was longer. In addition, though many works have been done about the influence of strain ranges, not a universally quantitative assessment of strain ranges was given. Therefore, a TMF lifetime model is desperately needed to understand the failure behavior of TBC systems under service conditions and to predict the lifetime of the components.

The main purpose of the present work was to investigate the influence of strain ranges and phase angles on TMF behavior of TBC systems and find out a universally quantitative TMF lifetime model of TBC systems considering the two factors.

1 Experiment

In the present study, the columnar crystal superalloy MGA1400 was chosen as the substrate material and was manufactured to TMF cylindrical specimens with a gauge diameter of 6 mm and a gauge length of 15 mm according to Fig.1. Then, all the substrates were grit blasted by alumina powder with 80 mesh grain size distribution. Afterwards, the substrate was deposited by High Velocity Oxygen Fuel (HVOF) with a CoNi32Cr32Al8Y0.5 alloy as the BC with the thickness between 80 μm and 100 μm. The 8 wt% yttria Y_2O_3 partially stabilized ZrO_2 (YSZ) ceramic TC was deposited by means of air plasma spraying (APS) with thickness between 300 μm and 320 μm, as shown in Fig.2.

The TMF tests were performed on an MTS810 closed-loop servo-hydraulic test 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. Cooling was mainly achieved by thermal conduction into the water cooling specimen grips and forced by blowing compressed air. Axial strain measurements were obtained using a self-supporting extensometer which has a gauge length of 16 mm and was supported with ceramic rods.

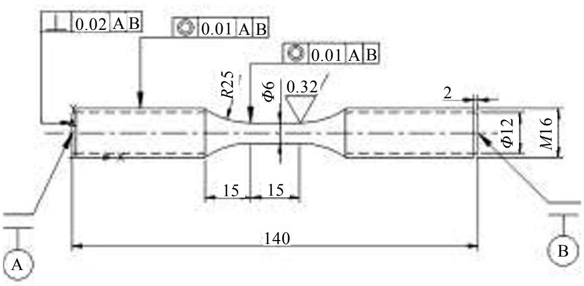

Fig.1 TMF specimen geometry

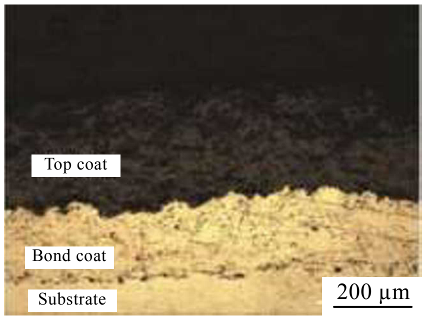

Fig.2 Microstructure of the as-deposited TBC

Temperature control was conducted with a thermocouple enlaced in the middle of the gauge length. In order to reduce the amount of time that one single specimen remains in the TMF tests, the specimens were isothermally pre-oxidized at 1000 °C in air for 100 h prior to the TMF experiments. To closely represent turbine engine conditions, a dwelling time 5 min at the highest temperature was included in tests (Fig.3).

Two kinds of TMF loading were used: IP where the maximum mechanical strain coincides with the maximum temperature and OP where the maximum mechanical strain is attained at the minimum temperature. TMF tests were carried out in the temperature range of 200~900 °C with a cyclic period of 900 s under mechanical strain control. The mechanical strain ranges, $\Delta\varepsilon_{mech}=\varepsilon_{max}-\varepsilon_{min}$, are –0.45%, –0.30% and 0.30%, as listed in Fig.3.

After the TMF tests, the specimens were embedded in an epoxy resin before cutting to reduce the possibility of damage, and then longitudinal and horizontal sections of the tested specimens were cut. Then these sections were metallographically prepared and observed by the optical microscopy (OM) and scanning electric microscopy (SEM).

2 Results

2.1 TMF lifetime

TBC spallation occurred after various numbers of cycles and the spallation geometries were observed in Fig.4. It was shown that phase angles and strain ranges have obvious influence on TMF lifetime (TBCs spallation), especially strain ranges. Under the same strain range 0.30%, the TBC coating got spalled after 69 cycles under IP tests (sample 3 in Fig.4) and a little shorter lifetime of 65 cycles under OP tests (sample 2 in Fig.4). With increasing compressive strain range to –0.45%, the coating OP life was shortened to only 5 cycles (sample 1 in Fig.4).

2.2 Cyclic stress-strain response

Fig.5 shows the comparison of hysteresis loops of 1st cycle and half life cycle under various TMF tests. It was shown that OP tests lead to severe inelastic deformation during the first cycle. The compressive stress increases up to 990 °C and thereafter it decreases despite the continuously