Plasticity, Failure and Fatigue in Structural Materials-from Macro to Nano: Proceedings of the Hael Mughrabi Honorary Symposium

Edited by:

K. Jimmy Hsia
Mathias Göken
Tresa Pollock
Pedro Dolabella Portella
Neville R. Moody

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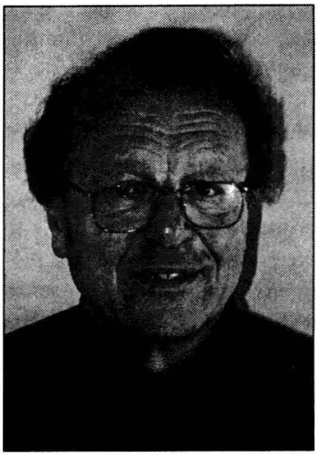
Preface

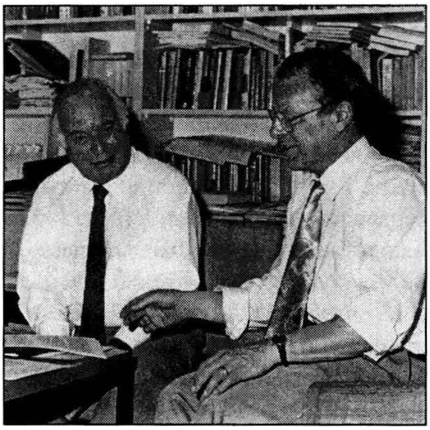


This proceedings volume collects papers from the Haël Mughrabi honorary symposium presented at the TMS 2008 Annual Meeting & Exhibition in New Orleans. This symposium has been organized in recognition of Professor Mughrabi's outstanding contributions to the field of the mechanical properties and microstructure of materials. Professor Mughrabi, of the University Erlangen-Nürnberg in Germany, celebrated his 70th birthday in 2007 in good health and as a very active scientist. Although he retired officially in 2002, he is still present daily at the institute in Erlangen and, sometimes, even the weekends are too short to fulfill his research duties and activities.

Professor Mughrabi's life and career display an internationally grown-up and embedded person who always had very strong ties to people all over the world. He was born on June 2, 1937 in Stuttgart, Germany to an Egyptian father and a German mother. He grew up and was educated in Jerusalem, Palestine and Cairo, Egypt. The picture at right shows him (upper row, second from left) in 1952 in Mohamed Hamza among his classmates. In 1955 he went back to Germany and started an apprenticeship at the Robert Bosch Company in Stuttgart. After finishing, he studied physics at the University Stuttgart and later on began his scientific career as a research associate at the Max-Planck-Institut für Metallforschung, Stuttgart. He finished his doctorate in physics in 1970 and remained in Stuttgart until 1984. From 1978 to 1979, he was appointed to a visiting professorship at Cornell University in New York, United States. In 1984, he accepted an offer to a professorship of materials science and engineering at the Friedrich-Alexander-University Erlangen-Nürnberg. There Professor Mughrabi became head of the Institute for General Materials Properties. He held this position until his retirement in 2002 when Mathias Göken took over the responsibility. During his work at the University in Erlangen, Professor Mughrabi had many roles, such as department head, engineering school dean, and elected

member of the university senate. In Erlangen, he worked closely with Professors Bernd Reppich (left photo, right), Hans-Georg Sockel (left photo, middle) and Wolfgang Blum.

For more than four decades, Professor Mughrabi has made numerous seminal contributions to the field of mechanical behavior of materials and especially to improving our understanding of the correlation between microstructure and mechanical behavior. In particular, he has done fundamental studies on the mechanisms of plastic deformation and fatigue, based on dislocation mechanics. His pioneering work on understanding the occurrence and interaction of persistent slip bands in cyclic deformation and his composite model are well known. His research also focused on engineering aspects as materials for high temperature applications. On nickel-base superalloys, the rafting phenomenon and the influence of the lattice misfit on the mechanical behavior have been studied in detail including modern analytical techniques. Professor Mughrabi always had strong exchanges with scientists from abroad, for example with Professor Frank Nabarro (right photo, left) at a visit in Erlangen in 1994.



More recently, as nanoscale materials and phenomena such as size-effects and strain-gradient-plasticity have become prominent in the field of materials research, Professor Mughrabi, like many of his colleagues, has worked to uncover the magic of nanomaterials; he became the first to look in detail on the fatigue behavior of ultrafine-grained metals. Another field of his recent interests is the very high cycle fatigue behavior of metals and alloys, where he has made important contributions in the understanding of failure beyond the classical endurance limit. These different fields of research are highlighted in this symposium with contributions from many highly recognized researchers.

Professor Mughrabi belongs to the rare group of researchers who perform both experimental and theoretical research. Perhaps it is this trait that makes him very insightful when it comes to understanding mechanical behavior of materials. He published more than 280 papers in international journals and is among the ISI

Highly Cited authors. He received many highly recognized honors, including the Masing award (1973) and Heyn-Denkmünze (2000) of the Germany Society for Materials Research; the Hsun Lee Lecture Award (2006) of the Institute of Metal Research of the Chinese Academy of Sciences, Shenyang, China; and the Edward De Mille Campbell Memorial Lecture Award 2008 of ASM International. He served as a member on numerous editorial and advisory boards for international journals. From 1994 to 2000, he was chairman of the international conference series ICSMA - International Conference on the Strength of Materials. His dedication to research and also to the education of students has always been very strong and positive.

We all thank Professor Mughrabi sincerely for his extensive commitment to science and to the education of students, and hope that he still can contribute and support the worldwide materials science community in the future as he has done in the last four decades. We wish him all the best for the coming years.

Mathias Göken
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DAMAGE OF APS-TBCS IN THERMOMECHANICAL FATIGUE TESTS

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Abstract

Thermal barrier coatings (TBCs) are applied to gas turbine blades to increase maximum service temperature. The performance of TBCs under thermomechanical fatigue (TMF) is governed by the TMF cycle, the thermal mismatch between TBC and substrate, and microstructural changes (e.g. sintering of the TBC, oxide scale growth, interdiffusion processes).

In the present work a TBC system comprising air plasma sprayed ZrO_2/8wt.-% Y_2O_3 with NiCoCrAlY bond coat on CMSX-4 substrate was subjected to out-of-phase TMF with different high temperature dwell times and mechanical load amplitudes. Some specimens were pre-oxidised before TMF testing.

TMF without dwell time resulted in fatigue failure of the base material. Pre-oxidation before TMF testing with the same cycle did not significantly change the failure behaviour. However, sufficiently long dwell times lead to TBC spallation before fatigue cracking of the base material. The oxidation and fatigue related processes of crack formation and propagation under TMF loading are discussed.

Introduction

Improving gas turbine power output and efficiency by increasing turbine inlet temperatures is possible by appropriate cooling concepts combined with thermal barrier coatings applied on blades and vanes in gas turbine. Currently used TBCs typically consist of a ceramic top coat and a metallic bond coat [1-3]. During operation cycle the hot section components of gas turbines undergo complex thermal and mechanical loadings. As a result, the thermomechanical fatigue is one of the main lifetime limiting factors, especially for turbine blades.

The performance of the TBC under TMF is related to the thermal and mechanical strains generated as well as to the oxidation of BC. It is important to identify the parameters which affect the crack growth mechanism and thus the life-time of thermal barrier coatings [4,5]. However, studies on TMF behaviour of TBC systems reported in the literature are limited and differences in experimental procedure make the comparison of published results very difficult. Both the failure by spallation of TBC and the fatigue failure of bond coat and base material have been reported [6, 7], but systematic investigations on the type and details of failure are not available up to now.

The aim of the present study is to identify the failure modes and damage mechanisms of TBCs under TMF loading in relation to the cycle shape, and particularly to the presence of high temperature dwell time as well as to different pre-oxidation treatments.

Experimental

For TMF tests hollow cylindrical specimens of a TBC-coated single crystal Ni-base superalloy CMSX-4 with 6.85 mm internal diameter, 10 mm external diameter over the gauge length of 20 mm were used. The TBC system consisted of a NiCoCrAlY bond coat (PWA 286) and a plasma-sprayed ZrO_2/8wt.-% Y_2O_3 thermal barrier coating (Metco 204 NS). Experiments were conducted using an universal testing machine (Instron, model 8802) with a 100 kN static/50 kN dynamic load cell equipped with an 24 kW - infrared furnace (24 halogen lamps, 1 kW each) from Xerion GmbH. To achieve a uniform temperature distribution throughout the specimen, IR lamps were arranged in 3 control circuits with 8 lamps over the each circuit. Cooling was performed by external compressed air flow. The temperature was controlled within ±10°C along the gauge length using 3 pyrometers, which were calibrated with Pt/Pt-Rh-thermocouples. The specimen deformation was monitored using high temperature extensometer from MTS systems GmbH. Before the tests the samples were coated with iron oxide to improve the absorption of the IR radiation to the specimen surface.

The TMF tests were carried out under strain control with a mechanical strain range of 0.6% and a temperature range of 350°C-1050°C. The symmetrical out-of-phase (OP) TMF test represents a superposition of cyclic mechanical and cyclic thermal load components with a phase angle of 180° between both load cycles. Two OP cycle shapes were used: (i) consisted of 6 min heating, 6 min cooling and 5 min dwell time at T_{min}= 350°C, and (ii) had a dwell time of 120 minutes at T_{max} = 1050°C. With some specimens pre-oxidation treatment at 1050°C for 300 and 1000 hours was performed before the TMF test. The experimental procedure was carried out according to the European Code-of-Practice for strain controlled TMF testing [8].

The microstructural investigations were performed after metallographic preparation using optical microscopy (Leica – MEF4M) as well as scanning electron microscopy (LEO 1530 – 'Gemini') for the high resolution imaging of the damage.

Results and discussion

TMF tests

Figure 1 shows the maximum and the minimum stress as a function of cycle number for as-coated and pre-oxidized (300 and 1000 hours at 1050°C) samples under TMF conditions without dwell time at high temperature (Figure 1.a) as well as for as-coated samples under TMF with dwell time (Figure 1.b). In all cases the maximum and minimum stresses are shifted in the direction of tensile stresses with increasing cycle number because of the relaxation processes at high temperature, a phenomenon typically observed for OP TMF [5].

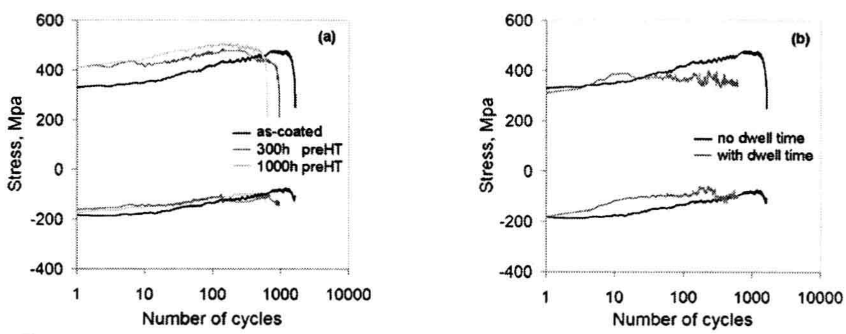

Figure 1. Evolution of maximum and minimum stresses under OP TMF with 0.6% mechanical strain range and temperature cycles between 350 and 1050°C.

The sharp decrease of the tensile stresses during the last cycles of the TMF tests without dwell time provides evidence of pronounced fatigue crack growth. The failure of base material occurred after 1620 cycles for as-coated sample. Pre-oxidation treatment for 300 h and 1000 h at 1050°C led to a decrease in lifetime to 948 and 615 cycles, respectively. This result might be