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Damage Evaluation of Thermal Barrier Coatings Under High Temperature Low Cycle Fatigue Conditions

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Abstract: Thermal Barrier Coatings (TBCs) are multi-layer protective coatings used in the hot section components such as combustor and turbine of advanced gas turbine engines to protect them from degrading effects of hot gases. Today, due to lack of a reliable life time assessment, the potential of these coatings cannot be fully used. Understanding of damage mechanisms of thermal barrier coatings is the key factor to increase durability and reliability. In this paper TBCs have been shortly introduced and then damages resulting from high temperature low cycle fatigue tests and their probable reasons have been explained. Inconel 100, a directionally solidified nickel based superalloy as a substrate, approximately 120 µm thick NiCoCrAlY bond coat and approximately 200 µm thick 7 wt % Yttria Partially Stabilized Zirconia ceramic top coat have been used. Both layers are deposited by EB-PVD technique. The results of the tests show that number and size of the cracks changes with the strain range. Cracks initiate in the TGO/BC interface and propagate into the substrate perpendicularly to the loading axes. Ceramic thermal barrier coating retards the formation of cracks. On the surfaces of the specimens having only bond coat, rumpling which is a typical service damage of turbine blades has been detected.

Keywords: Gas turbine, Thermal Barrier Coating, Low Cycle Fatigue

Introduction

Blades and vanes of the high pressure turbine section of aero engines are among the most highly stressed parts in engineering components. Internally cooled aerofoils of Ni-base superalloys operate at temperatures of about 1000°C with short-term peaks yielding even 1100°C which is close to 90% of the alloys' melting points [1-4]. These temperatures are maintained in service due to a highly sophisticated cooling technology by which however thermal energy is withdrawn from the aerofoils in the order of 1MW/m^2 thus reducing the overall fuel efficiency of the engine [1]. The necessity of a close control of materials temperatures can be expressed by the simple rule that creep life of turbine blades is halved for every 10 to 15°C increase in temperature [1,3]. Today turbine inlet temperatures exceed 1400°C [1,5]. But further increases in thrust-to-weight ratio of advanced aero engines will require even higher gas turbine inlet temperatures. Future developments aim to exceed 1600°C [5-9]. There is no doubt that this ambitious goal can only be met by usage of uneconomically extensive cooling techniques or by advanced high temperature materials.

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These alloys have matured over the years from wrought to cast, then to directionally solidified and single crystal alloys [1].

These alloy development approaches have enabled significant advances in material performance but further improvements appear unlikely since they now operate in environments where the temperature approaches 90% of their melting point. Furthermore, the design of more efficient cooling geometries within the component and film cooling approach of the component surface using drilled holes have also now matured [10]. The most promising approach is the use of a thermal barrier coating (TBC) system which thermally protects engine components and allows for their use at higher engine gas temperatures. The insulating properties of these coatings may lead to performance improvements by allowing a reduced cooling air flow at a given metal temperature or may improve lifetime of the components by reducing the metal temperature at a given cooling air flow. Furthermore, higher engine thrust can be achieved by allowing higher gas temperatures at a given cooling air flow [3,10,11]. With increased combustion temperature and decreased cooling air, fuel consumption decreases [2,5,11,12].

In this paper, TBC systems have been shortly described and then damages resulting from high temperature low cycle fatigue (HT-LCF) tests and their probable reasons have been explained.

Thermal Barrier Coating Systems

TBC systems typically consist of an insulating yttria partially stabilized zirconia (YPSZ) ceramic top layer exhibiting a low thermal conductivity, chemical inactivity in combustion atmospheres and possesses a relatively high coefficient of thermal expansion which is reasonably compatible with Ni-based superalloys. As zirconia is essentially transparent to oxygen ions at high temperatures, the metallic substrate providing blade geometry and structural properties is usually protected by an oxidation-resistant bond coat (BC) in order to minimize the environmental attack to a technically reasonable level. Although, by definition, the BC is supposed to provide adhesion of the YPSZ top coating to the substrate, the real bonding layer between the ceramic and the metallic coating is the thermally grown oxide (TGO), typically and preferably α–alumina, that forms during processing and due to bond coat oxidation in service. These four constituents of a TBC system; substrate, BC, TGO and YPSZ are all dynamic in nature and interaction of the components during service affects system performance and durability [8,13-22]. A sketch of a TBC system is depicted in Fig. 1.

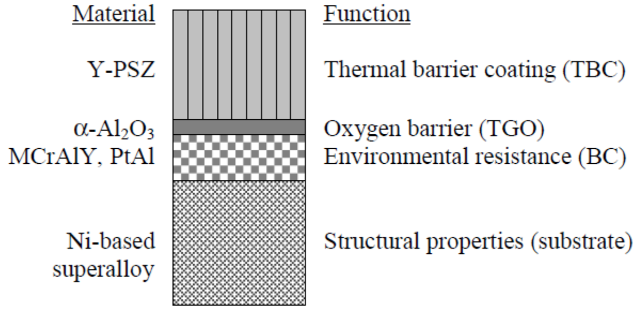

Fig. 1. Typical TBC system [13]

It is obvious that TBCs have an important role on the present applications and new generation engines. However, the potential of thermal barrier coatings cannot be fully used at present due to the lack of a reliable life time prediction of the coating. A thorough understanding of TBC failure mechanisms is key to increasing as well as predicting TBC durability. [23-24]. Life prediction models for TBC systems should take into account the damage accumulation due to fatigue in service and changes in material properties induced by time and temperature dependent processes.

Experimental

Cylindrical solid fatigue specimens with a thermal barrier coating system have been used. The whole length of the specimens was 90 mm and substrate diameter was 8 mm in the 12 mm long gauge length. One example specimen is shown in Fig. 2. As substrate material a directionally solidified nickel based superalloy (IN 100 DS) was used. The grains were oriented with the <100> direction close to the length axis of the specimens, which corresponds to the orientation of directionally solidified single crystal materials in turbine blades with respect to the direction of the centrifugal forces. The metallic BC is a NiCoCrAlY with a thickness of about 120 µm and the ceramic topcoat is a zirconia partially stabilized with 7-8 wt% yttria (YPSZ) with a thickness of about 220 µm. All materials were processed at the German Aerospace Center in Cologne.

Strain controlled isothermal LCF tests were carried out on a computer controlled servo-hydraulic test machine. An Instron SFL three zone split furnace (type SF177) was used to heat the specimens, and an Eurotherm temperature controller (type 2704) was used to control the furnace and specimen temperature. Test temperature was 950ºC. Strain was measured by an MTS high temperature extensometer (type 632.51F-04) with a gauge length of 12 mm. The LCF tests were carried out with a triangular waveform and a frequency of 1 Hz. After LCF tests the microstructure of the specimens was investigated using a Leica Wild M8 model stereo optical microscope and a LEO Gemini DSM 982 scanning electron microscope (SEM).

Fig. 2. A TBC coated LCF specimen

Results and Discussions

Specimens which were tested in as coated condition and the test parameters are given in Table 1. The defects in form of oxidized cracks have been observed in specimens SP1, SP2, SP6, SP7, SP 8 and SP 9. An example of the observed defects is given in Fig. 3. Length sections of these specimens revealed that the cracks originated in the BC, preferentially at the interface between BC and TGO, and propagated perpendicular to the load direction into the substrate.

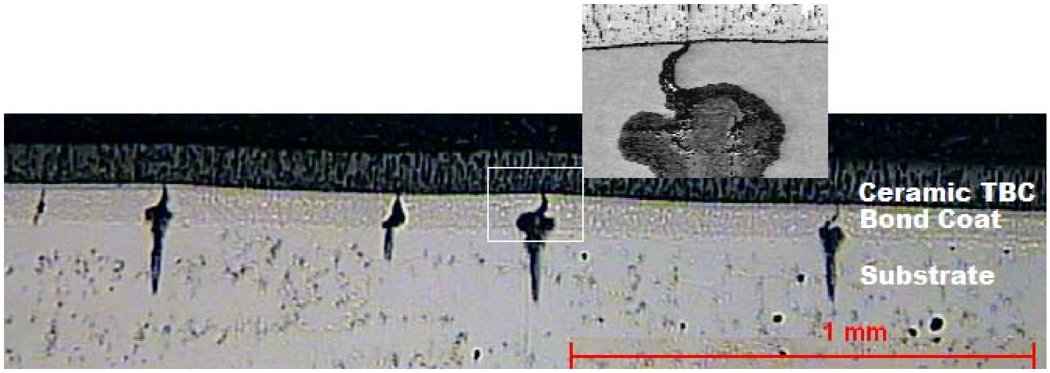

Fig. 3. Some of the defects in SP2

Table 1. List of as coated specimens and LCF test conditions

Specimen	Loading	Strain , %		Load, kN		Δε, %	ΔF, kN	Cycles
		Max.	Min.	Max.	Min.			
SP1	tension-comp.	+0.20	-0.20	8.5	-8.0	0.40	16.5	120000
SP2	tension-comp.	+0.25	-0.25	11.6/8.3	-9.2/-12.1	0.50	20.8/20.4	225000
SP3	comp.-comp.	-0.10	-0.25	-1.6	-7.4	-0.15	-5.8	225000
SP4	tension-tension	+0.25	+0.10	9.6/10.0	2.8/3.2	0.15	6.8	225000
SP5	comp.-comp.	-0.02	-0.25	-1.3/1.4	-8.0/-6.8	-0.25	-6.7/8.2	475000
SP6	tension-comp.	+0.20	-0.20	7.2	-8.5	0.40	15.5	225000
SP7	tension-comp.	+0.10	-0.35	5.5/7.3	-12.6/-10.5	0.45	18.1/17.8	225000
SP8	tension-comp.	+0.35	-0.10	12/9.7	-4.7/-7.0	0.45	16.7	225000
SP9	tension-comp.	+0.30	-0.20	12.6/9.6	-9.5	0.50	22.1/19.1	225000

When specimens SP2 and SP6 are compared; it can be seen that after same number of cycles, the specimen SP2 that tested under higher strain amplitude accommodates more and bigger defect, Figs. 3 and 4. It can conclude that, with the same number of cycles, the load i.e. mechanical stress has a significant effect on the formation of defects.

To investigate the effect of loading direction, the specimen SP1 has been chosen as a reference since it accommodates some defects. The specimen SP4 was tested under a tension-tension loading in a strain range between +0.10% and +0.25%. The maximum loads of two specimens have been compared in Fig. 5 and the specimen SP5 was tested under a compression-compression loading in a strain range between -0.02% and -0.25%. The minimum loads of two specimens have been compared in Fig. 6.

As seen in the diagrams, SP4 experienced a higher tension loading than that of SP1 and SP5 experienced almost the same even sometimes higher compressive loading than that of SP1. Also the specimens SP4 and SP5 experienced more number of cycles than SP1. However no damage has been observed in those tension-tension and compression-compression specimens. Before concluding that only compression-compression loading or tension-tension loading (in spite of having more number of cycles) does not result in any damage, it's necessary to focus on the differential of maximum and minimum strains (Δε) applied to the specimens SP4 and SP5. Δε value for these specimens is 0.15% and 0.25% respectively while for the specimens having cracks (SP1, SP2 and SP6) is 0.40% and 0.50%.

For this reason, to determine the effect of only tensile and only compressive loadings on the crack formation, specimens should be tested under conditions that $\Delta\varepsilon$ value will not be less than 0.40%. Since the strain having a magnitude of 0.40% only in tension or compression will generate very high stresses which will result in fracture of the specimen before a TBC system failure, SP7 has been tested under +0.10% and -0.35% strain range and SP8 been tested under +0.35% and -0.10% strain range.

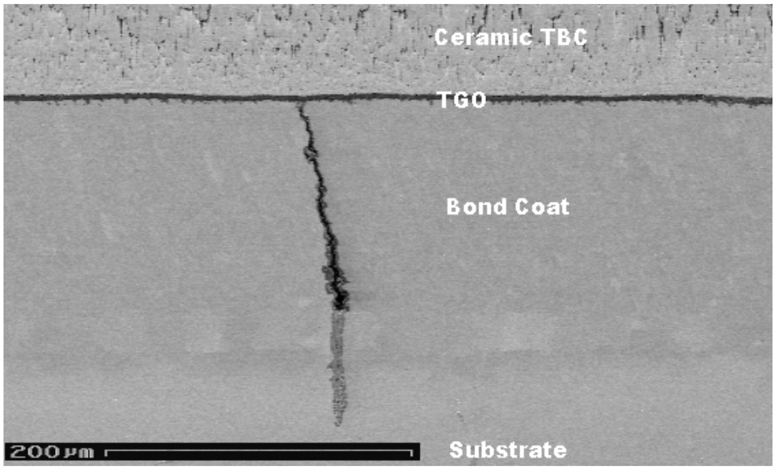

Fig. 4. Only one defect observed in SP6

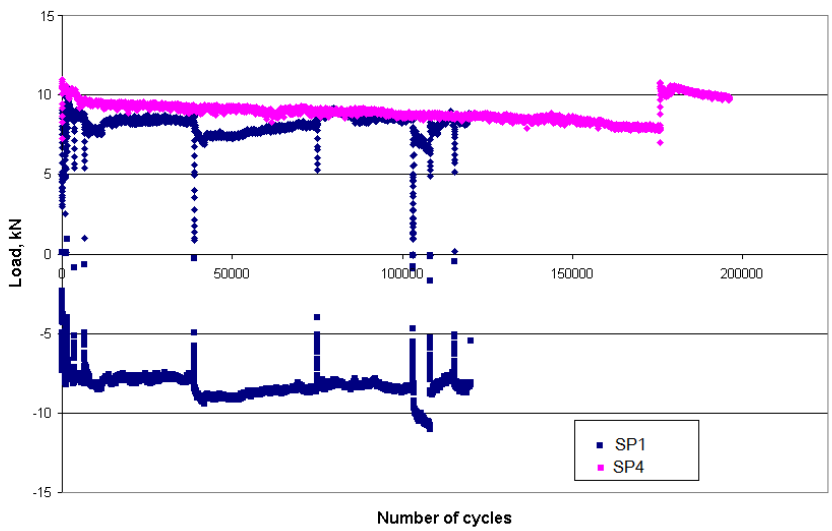

Fig. 5. Comparison of maximum loads of SP1 and SP4

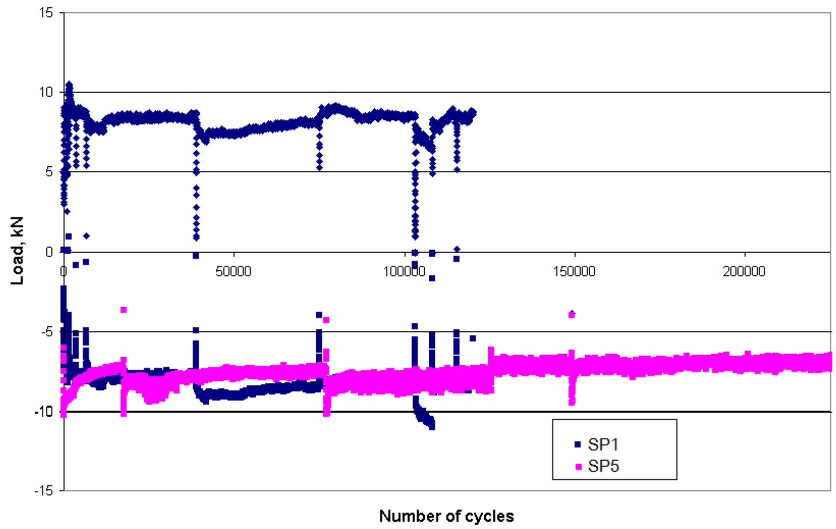

Fig. 6. Comparison of minimum loads of SP1 and SP5

Existence of cracks in both specimens shows that, not only the absolute magnitude of mechanical stresses but also the difference between maximum and minimum stresses plays an important role on the crack formation under high temperature LCF testing conditions. For example while 8.5 kN tensile and 8.0 kN compressive loads in SP1 created some cracks, the tensile loads of 9.6-10.0 kN in SP4 or compressive loads of 8.0 kN in SP5 could not create any cracks. Because the difference between maximum and minimum loads (ΔF) in SP1 is 16.5 kN while this value is only 6.8 kN in SP4 and 6.7-8.2 kN in SP5.

Table 2. List of specimens having only bond coat and LCF test conditions

Specimen	Loading	Strain , %		Load, kN		Δε, %	ΔF, kN	Cycles
		Max.	Min.	Max.	Min.			
SP10	tension-comp.	+0.25	-0.25	9.1	-14.8	0.50	23.9	47870
SP11	tension-comp.	+0.18	-0.18	11.1	-4.1	0.36	15.2	200000
SP12	tension-comp.	+0.07	-0.28	4	-10	0.35	14	225000

The results obtained from the specimens having only bond coat show the role of ceramic thermal barrier coating on the defect formation under high temperature LCF testing conditions (Table 2). SP10 has been tested under the same loading conditions with A2 having a TBC layer and revealing some cracks. Test has been automatically stopped before reaching 50000 cycles and the length section of the specimen showed many cracks some propagating into the depth of specimen, Fig. 7. This concludes that the ceramic thermal barrier layer retards the formation of cracks. Besides, even though the other only bond coated specimens (SP11 and SP12) have been tested under lower Δε and ΔF values and during the same number of cycles with A6, they have more number of cracks and this results support the conclusion above.

On the outer surfaces of LCF specimens having only bond coat, rumpling has been observed, Fig. 8. Rumpling of metallic protective coatings is frequently observed in turbine blades in service. Valleys in the rumpled surfaces are stress concentration zones and initiation points for fatigue cracks propagating into the substrate. Another harmful consequence of rumpling is that it accelerates oxidation and aluminum depletion in the coating by increasing surface area imposed to oxidizing environment [25]. Under laboratory conditions, rumpling is observed in thermal mechanical fatigue, thermal gradient mechanical fatigue and even in thermal fatigue tests [26]. There is a heating-cooling cycle i.e. thermal fatigue under all these test conditions. The observation of similar rumpling on the LCF specimen which have only bond coat implies that such a deformation can be created under isothermal high temperature LCF conditions.

The last group of LCF specimens (Table 3) has been pre-heat treated at 1000ºC for 250 hrs and 500 hrs and then tested to examine the effect of time at high temperature. In 250 hrs aged specimen (SP13) differing from the others, cracks propagated not only perpendicular to the loading axis but also parallel to the loading axis in between bond coat and substrate so called diffusion zone, Fig. 9. But 500 hrs aged specimen (SP14) does not show this kind of crack feature. The microstructure of both specimens showed significant changes due to the increased time at high temperature.

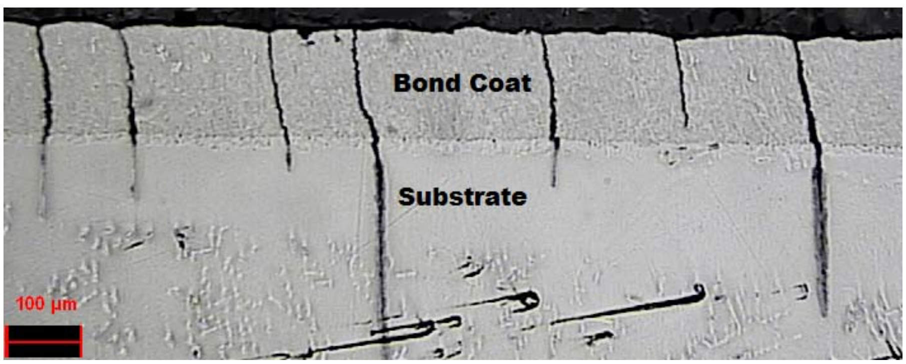

Fig. 7. Length section of the SP10

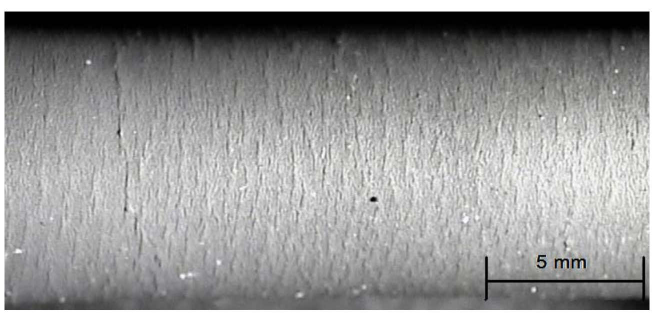

Fig. 8. Rumpling on the LCF specimen having only bond coat

Table 3. List of pre-heat treated specimens and LCF test conditions

Specimen	Loading	Strain , %		Load, kN		Δε, %	ΔF, kN	Cycles
		Max.	Min.	Max.	Min.			
SP13	tension-comp.	+0.25	-0.25	10.0/7.2	-10.0	0.50	20.0/17.2	225000
SP14	tension-comp.	+0.25	-0.25	9.6/7.6	-12.0/-13.6	0.50	21.6/21.2	225000

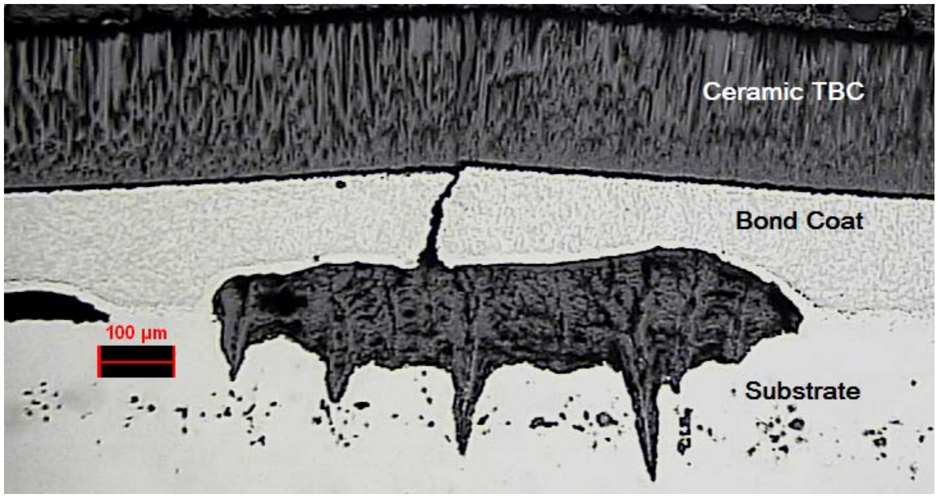

Fig. 9. An example of the crack propagating parallel to the loading axes

As mentioned before the cracks originated at the interface between BC and TGO, and propagated perpendicular to the load direction into the substrate. FE calculations show that in a TBC system highest stresses occur in the TGO layer [27]. Similarly in high temperature LCF test, the highest stresses have been calculated in the TGO layer. Under a given strain, having the highest Young's module element of the TBC system, the highest stresses occur in the TGO layer, thus cracks initiate at BC/TGO layer. Fig 10 shows the calculated stresses in ceramic TBC layer, TGO, BC and superalloy substrate under 0.20% and 0.25% strain at 950ºC.

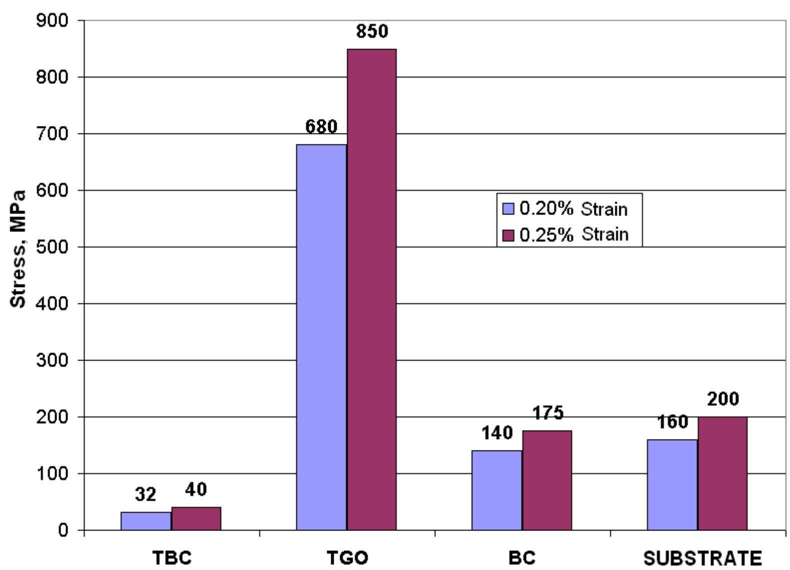

Fig. 10. Calculated stresses in the TBC system under 0.20% and 0.25% strain

Under high temperature LCF test conditions, the ceramic coating was not spalled and even delaminated. Some cracks have been observed on the outer surface of ceramic coating in SP2, SP9 and SP13, Fig. 11.

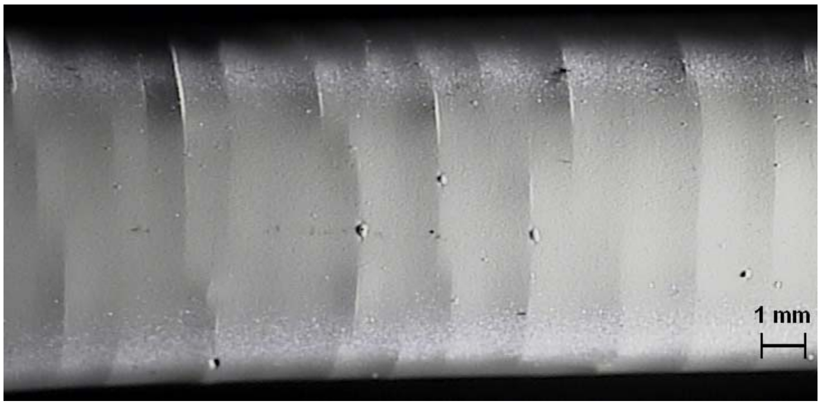

Fig. 11. Cracks on the outer surface of SP2

Conclusions

Within the specimens with ceramic thermal barrier coating, cracks were observed in the specimens tested under ±0.20% ($\Delta\varepsilon$ = 0.40%) and ±0.25% ($\Delta\varepsilon$ = 0.50%) strain range. Number and size of the cracks increase with the increased strain range. Cracks initiate at the interface between bond coat and thermally grown oxide layer and propagate perpendicular to the load direction into the substrate. In case the specimens which were tested under tensile or compressive mean stress are tested under the same ε_{max} or ε_{min} values with the specimens that were tested under zero mean stress, no cracks were detected. In this case cracks occur only under conditions where $\Delta\varepsilon > 0.40\%$.

The results obtained from the specimens having only bond coat imply that ceramic thermal barrier coating retards crack formation while cracks occur in these specimens under much lower strain ranges and after less number of cycles. After high temperature low cycle fatigue tests rumpling, typical service damage of turbine blades, was detected.
Unlike the other specimens, cracks propagating parallel to the loading axes was observed in the 250 hrs heat treated specimen. Also the pre-heat treatment of the specimens i.e. increased time at high temperature caused significant changes in the microstructure of the thermal barrier coating system.

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