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INFLUENCE ON LOW CYCLE FATIGUE PROPERTIES OF BOND COAT OXIDATION FOR A THERMAL BARRIER COATING

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ABSTRACT

Influence on the LCF life of a Thermal Barrier Coating has been studied for an air plasma spray (APS) partially stabilised Zirconia (PSZ) top coat together with a NiCoCrAlY APS bond coat sprayed onto a nickel base superalloy. The study has been focused on LCF tests for specimens pre-oxidised to different TGO (thermally grown oxide at the interface between top and bond coat) thicknesses. Comparisons of fatigue behaviour between coated and uncoated materials for both as received and heat treated material has been evaluated. Materials used in the present study are ZrO_2 + 8w/oY_2O_3 top coat, Ni171 bond coat and H230 substrate. The results show a decreasing trend regarding fatigue life when pre-oxidised material is tested. It is also shown that an applied bond coat slightly reduces the fatigue properties in comparison to the uncoated substrate. At 850°C the effect on fatigue life of an oxidised bond coat is significant but at 500°C no large variations regarding fatigue life can be observed. For all cases the Coffin-Manson expression for fatigue life can be used since delamination or spallation do not occur. It is also shown that the crack initiation sites mainly are located to the interface between top coat and bond coat. Regarding the substrate different mechanisms govern the hardening or softening behaviour at various temperatures. At lower temperatures dislocation movement is hindered by small precipitates in the Ni-bas superalloy but at 850°C the dislocations can cross slip and pass by without hardening behavior of the material.

KEYWORDS

thermal barrier coating, NiCoCrAlY, oxide growth, low cycle fatigue, Coffin-Manson law

INTRODUCTION

Thermal barrier coatings (TBC) are important for gas turbine manufacturers when increased efficiency and lower emissions are required from the users of such systems in land based applications. The application in this case is coatings used in gas turbines for power generation. Thermal barrier coatings are already used in aeroplane engines, where military aircraft dominate the market. The differences between land based and airborne turbines are cycle time, fuel type and inspection intervals. These factors sets stronger demands with respect to long time stability and integrity for the materials used in coating systems for land based gas turbines. Therefore ongoing projects aim to develop durable TBC systems and reliable models regarding TBC life in order to fully be able to take advantage of the benefits a TBC can give.

A thermal barrier coating system is normally composed of two layers on a substrate. The top coat is applied in order to serve as a thermal insulator for the underlying material. The drawback is that APS

Zirconia, which is used for its low thermal conductivity, serves as an excellent diffusion path for oxygen. Therefore an oxide forming material has to be applied below the ceramic top coat. This layer is normally composed of one or more of the metals Ni or Co together with Cr, Al and also rare earth metals as Y. Other combinations are present. The alloy can be sprayed in air or vacuum or deposited in other ways on the metallic substrate. The substrate is the load carrying component. It can be a combustor, vane or a turbine blade. The top coat can have a thickness of 350µm up to 2mm, whilst the bond coat normally is sprayed to a thickness between 100µm and 200µm.

The aim of the present study is to clarify what influence a thermal barrier coating will have on the fatigue life for a nickel base superalloy. This is done for material pre-oxidised to interface TGO between 1 and 8 µm in order to achieve results valid for material subjected to conditions experienced in a gas turbine.

EXPERIMENTAL PROCEDURE

The experiments were performed on a material system built up of a 350µm thick PSZ top coat (ZrO_2 + 8w/oY_2O_3) and a 150µm thick bond coat (Ni171 – NiCoCrAlY) both air plasma sprayed onto a nickel base substrate (Haynes 230[1]), see figure 1. After coating at VOLVO AERO[2] the material was heat treated at 1000°C ± 5°C for times sufficiently long to produce thermally grown interface oxides with thickness between 1 and 8µm. Comparisons with previous studies made it possible to predict the oxide growth rates and thus the oxide thickness at different times of oxidation [1]. The material was heat treated in flowing air[3] at a flow rate of 0,5 l/min in order to get a predictable environment. Afterwards the oxide thickness was determined on cut and polished samples using an optical microscope. After heat treatment the material was fatigue tested together with non heat treated material.

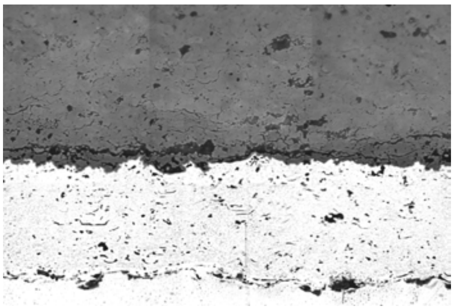

Figure 1: Polished cross section over an air plasma sprayed thermal barrier coating used in the present study. The upper (dark grey) layer is the ceramic top coat. In the middle the metallic NiCoCrAlY bond coat is found. At the bottom the interface between bond coat and the nickel base substrate can be seen. The TC has inherent defects, pores. These are the black spots in the dark grey layer. In the BC an oxide network is present. This is due to the spray process when the molten metal drops are in contact with the surrounding air. Magnification 150x.

Cyclic tests were performed in an MTS 160 kN test rig fitted with the INSTRON 8800 controller, alignment equipment and LCF software together with an MTS high temperature furnace and high temperature extensometer. In order to control the temperatures an external signal from the thermocouple was logged into the computer system via an Eurotherm retransmitter. Low cycle fatigue tests were then performed in strain controlled mode with control of total strain between 0,4 and 1,2%, R = -1 and a strain rate of 0,4 / min. For a total strain range of 0,008 the cyclic frequency is approximately equal to 0.5 Hz. Thermocouple mounting and LCF sample geometry were performed in accordance with ASTM specifications [2, 3]. After testing the specimens were cut and polished for examination with light microscopy and scanning electron microscopy (SEM).

[1] From Haynes International, USA
[2] VOLVO AERO, Trollhättan Sweden. http://www.volvo.com/aero/default
[3] *Technical air,* Trade mark of Air Liquide

RESULTS

Oxide growth

The oxides formed during heat treatment in the present study consist mainly of Alumina. Some Ni, Cr and Co can also be seen in the outer layers for longer oxidation times. This mixture of oxides tends to grow faster than pure Alumina. It has earlier been shown that the oxide formed with time is of spinel type [1, 4]. The oxide thickness after initial oxidation is shown in Table 1.

TABLE 1
RESULTS FROM INITIAL HEAT TREATMENT / OXIDATION OF THE TBC SYSTEM.

Time @ 1000°C [hrs]	Approximate oxide thickness [µm]
0	0,5
100	1
250	4
400	6
1000	8

Fatigue Behaviour

Uncoated material

Uncoated material was tested in order to act as a reference for comparison to the TBC-layer added to a nickel base alloy. The response of HAYNES 230 to mechanical cycling is shown in figure 2. Life responses at the test temperatures are reported in figure 3 and 4. For comparison a separate LCF-test has been performed at room temperature. At this low temperature the material shows a softening behaviour and a fatigue life tenfold higher than at the elevated temperatures.

The hardening response of uncoated material is shown in figure 5. The hardening exponent at 500°C is achieved by fitting a straight line to the measurement data in figure 4. The strain hardening exponent (according to Rahmberg – Osgoods expression) is found to be n_f = 0,17. In figure 4 the elastic and inelastic behaviour for HAYNES 230 at 500°C is presented together with regression equations, i.e. data to a Coffin-Manson type of equation.

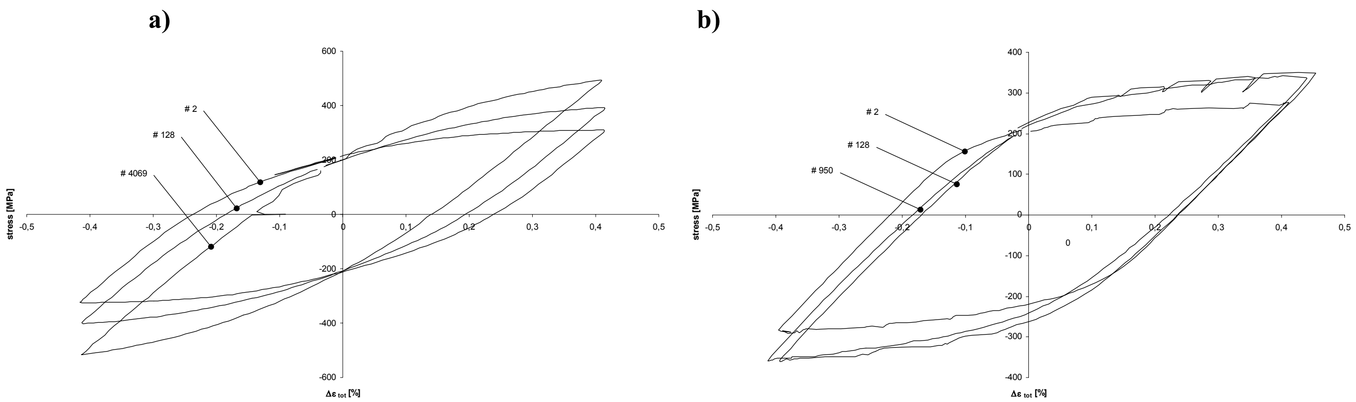

Figure 2: Hysteresis loops for HAYNES alloy 230 at a) 500°C and b) 850°C. It can be seen that the material shows a pronounced hardening behaviour at 500°C whilst at the higher temperature the the hardening of the alloy is not as striking.

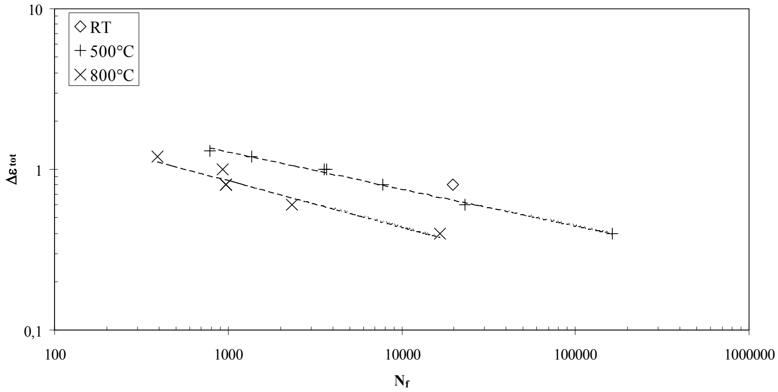

Figure 3: Plot of results for fatigue life versus total strain range of HAYNES alloy 230 at 500°C and 850°C. As a comparison measurements performed at room temperature has been added for $\Delta\varepsilon_{tot} = 0.8\%$.

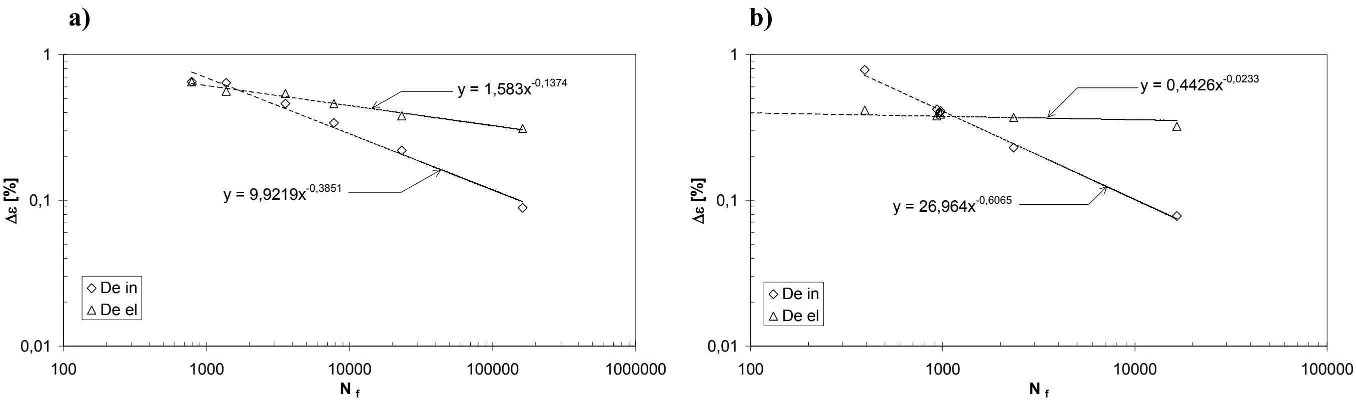

Figure 4: Elastic and inelastic behaviour for uncoated material at a) 500°C and b) 850°C.

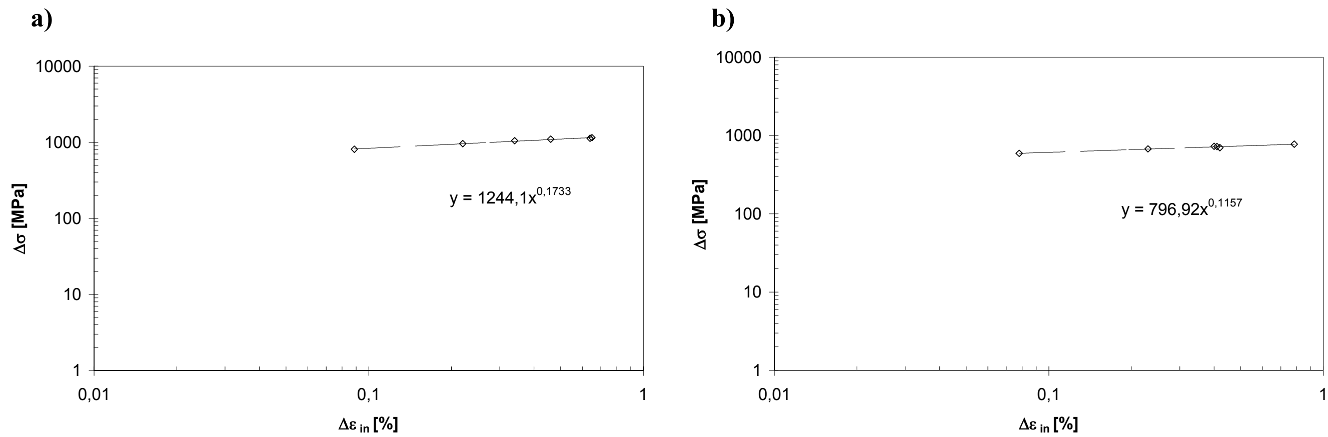

Figure 5: Cyclic stress versus strain response at a) 500°C and b) 850° for HAYNES alloy 230.

At850°C the hardening behaviour is not as significant as for the 500°C case. An analysis similar to the previous case will give a hardening exponent $n_f = 0.116$.

APS PSZ / NiCoCrAlY – coated material

For the coated nickel base alloy the change of fatigue life at $\Delta\varepsilon_{tot} = 0,4$ and R = -1 after pre oxidising for times up to 1000h is presented in figure 6. The figure shows data for both test temperatures in the present study (500°C and 850°C). In the figures four different states of TGO thickness are represented. The aim of the heat treatment has been to make an evaluation possible of influence from growth of interfacial and internal oxides on fatigue life. It can be seen that the influence of thermally grown oxides is significant only at 850°C. At the lower test temperature the results from mechanical testing do not show a clear trend for fatigue life as a function of TGO thickness.

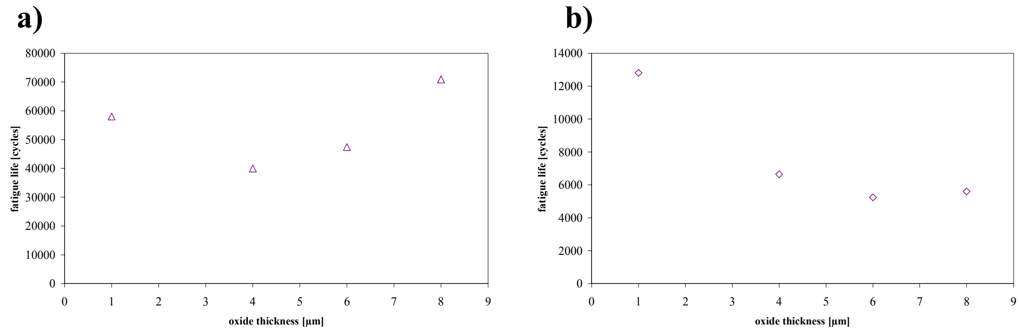

Figure 6: Results from fatigue tests of pre-oxidised TBC on H230. The tests are performed with $\Delta\varepsilon_{tot}$ = 0,4 and R = -1. Data stem from LCF tests at a) 500°C and b) 850°C.

Over the test range the fatigue life for uncoated material is superior that of TBC – coated material. This is valid both for variations in temperature and strain range. In most cases when a coating has been added the fatigue cracks initiate at the top coat / bond coat interface or within the bond coat. These findings are in accordance with what previously has been reported [5]. Typical appearance of interface cracks created at the two test temperatures is shown in figure 7. Cracks initiated in the bond coat propagate into the substrate and eventually causes specimen failure after successive load drop for constant strain amplitude. It has earlier been suggested [6] that large compressive stresses are believed to cause buckling of the TBC system if interface cracks are present. In this study no such phenomena are observed.

DISCUSSION

Fatigue of uncoated material

An attempt has been made to evaluate the fatigue performance of the nickel base alloy. It was shown that the material well follows a strain based fatigue model of Coffin-Manson type. This is valid for both coated and uncoated material. For the case of uncoated HAYNES 230 the comparison between model and test will be shown in figure 8. The agreement is good for strain ranges within the frame of the test. Strain ranges larger than those evaluated here are not of great interest, since the fatigue life at higher strain ranges and high temperatures is poor.

The material displays a hardening behaviour at 500°C. At 850°C the hardening behaviour is not as dominant. TEM studies show that the hardening at the lower temperature is due to dislocation pile up at small carbides. A study of material strained at the higher temperature shows a much less dense dislocation structure. Obviously the dislocations now can cross slip and by pass the small particles. In addition some growth of the existing carbides will occur during the fatigue cycle which will reduce the effect of hardening due to entangled dislocations.

Fatigue of coated material

Several authors have discussed the influence of oxides on the integrity of a TBC [6, 7, 8]. Oxidation of thermal barrier coatings is detrimental for the integrity of such a system. Exposure to oxide rich environments at high temperatures for long times causes degradation of the initially aluminium rich bond coat. Earlier studies have shown this and the reason is a combination of aluminium diffusion inwards into the substrate and aluminium consumed at the interface between bond and top coat [1, 9]. The reason for failure is said to be a change in oxide type since the Alumina will be mixed with nickel, cobalt and chromium rich oxides. These oxide types have lower tensile strength than Alumina and also poor fracture toughness.

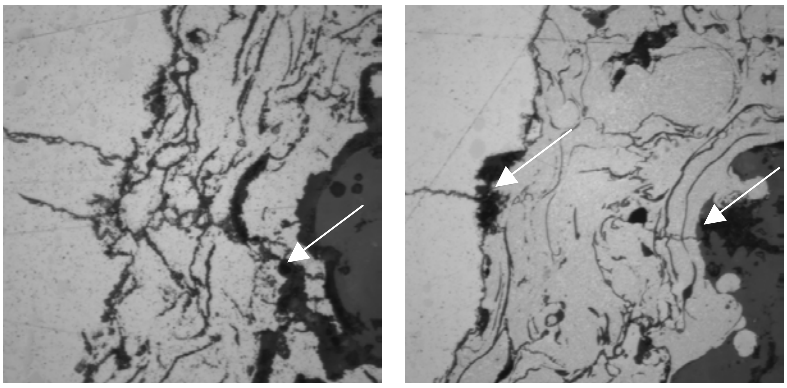

Figure 7: Cut sections of fatigue tested samples. The cracks originate at the interface between top and bond coat or at oxide particles within the bond coat. After this they grow and propagate into the substrate. Arrows indicate origin of cracks.

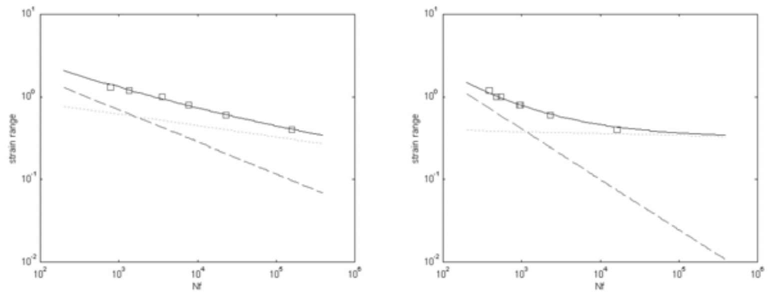

Figure 8: Comparison between model and experiments for a Coffin-Manson type of strain based low cycle fatigue law. Left figure represents 500°C, right 850°C. Open squares indicate experiments, dashed line elastic strain and dash dotted line represents inelastic strains.

After growth of a TGO layer stresses perpendicular to the interface arise, which will be harmful for the coating. The stresses are largest at heating and cooling. Simulations has been performed to show this [10]. The present investigation shows that for compressive stresses in the axial direction, no delamination cracks arise. Probably larger compressive axial stresses need to be present in order to really observe the effect of the low strength oxide types. If the coating system instead had been subjected to thermal cycling then the change in oxide composition would probably have had a detrimental negative effect on fatigue life. This would then also apply to thermomechanical fatigue.

It was earlier shown that the influence of bond coat oxidation on fatigue life was larger at 850°C than at 500°C. This might be explained by the brittle to ductile transition that takes place between 500 and 800°C [11] for the bond coat used in the present study. At the lower temperature the bond coat has mechanical properties more like the oxide since both are brittle. When the temperature is raised the bond coat behaves in a ductile manner and it can be suspected that the by temperature introduced mismatch between the oxide and the metallic bond coat promotes crack initiation.

By adding the TBC to the substrate the curves in figure 8 will be shifted to lower lives. The effect of an added coating is largest for low strain ranges. At high $\Delta\varepsilon$ the measurements from coated material seem to converge with results for the uncoated superalloy. The influence of an added coating is large for low $\Delta\varepsilon$. These findings have also been found by others [12]. This might be influenced by the fact that the fatigue life is more sensible to surface roughness when the strain or stress amplitude is low. In this particular case a coating has been sprayed onto a shot peened surface. This means that both the interface between substrate and bond coat as well as the one between bond coat and top coat is highly irregular. After oxidation the situation might be even worse, since oxide intrusions or protrusions might form at interfaces as the TGO grows thicker.

CONCLUSIONS

In the study a nickel base superalloy has been coated with APS TBC and the effect of this procedure has been investigated. The results can be summarised in the following points:

- For uncoated material the strain hardening exponent is found to be 0,17 at 500°C and 0,12 at 850°C.
- Addition of a thermal barrier coating onto a nickel base superalloy causes fatigue life to decrease for the material system.
- The crack initiates in the bond coat and propagates into the substrate.
- Heat treatment of the material system causes the bond coat to oxidise. The oxidation takes place both at the interface between top- and bond coat and within the bond coat itself. The later is mainly due to that an oxide network is present in the bond coat after manufacturing due to the spray process.
- The oxidation is responsible for the lower resistance to fatigue crack initiation and propagation. When radial fatigue cracks are present these are initiated in the bond coat and propagate into the substrate.
- Severe delamination cracks can not be observed after LCF testing, even though there seem to be some delamination at the interface oxides.
- It is possible to include the lowering of the fatigue life due to bond coat oxidation in a Coffin-Manson type of expression.

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