Materials Science and Engineering A 509 (2009) 111–114

Contents lists available at ScienceDirect

Materials Science and Engineering A

journal homepage: www.elsevier.com/locate/msea

Short communication

Stress rupture behavior of a thermal barrier coated AE 437A Ni-based superalloy used for aero turbine blades

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ARTICLE INFO

Article history:
Received 2 September 2008
Received in revised form 24 December 2008
Accepted 14 January 2009

Keywords:
Thermal barrier coating
Superalloy
Bond coat
Stress rupture
Rupture life

ABSTRACT

The stress rupture characteristics of bare and thermal barrier coated (TBC) superalloy AE 437A were determined in air at temperatures between 600 and 850 °C with both short and long term testing undertaken at 800 °C. Because the bond coat contributed an addition ~10% cross-sectional area and was able to support load, the higher stress, shorter term rupture lives of the TBC coated alloy exceed those for the bare material. However under lower stress, longer life conditions the ability of the bond coat to support loading was reduced, and the rupture lives of both bare and TBC coated alloy were similar.

1. Introduction

Recently it was reported by Ray and Das [1] that a thermal barrier coated (TBC) Superni C263 (Ni–20Cr–20Co–6Mo–3Ti–0.5Al–0.6C; wt.%) polycrystalline superalloy possessed improved 550–850 °C stress rupture characteristics compared to the unprotected material based on a Larson Miller Parameter (LMP) analysis. As comparison of the strengths of both the bare and TBC coated samples was based on the 3 mm by 4 mm cross-section of the superalloy alone, the improved strength was thought to be the result of load bearing capacity of the ~100 μm thick Ni–22Co–17Cr–12.5Al–0.6Y bond coat on the TBC samples which added a 12% increase in cross-section compared to the bare alloy. Xiao et al. [2], on the other hand, stress rupture tested the 5 mm diameter directionally solidified Ni_3Al-based alloy IC6A (Ni–8Al–14Mo–0.05B) samples with and without an ~40 μm thick Ni–12.3Co–17.3Cr–12.6Al–0.5Y–0.6Hf coating and found no difference in their 1100 °C—90 MPa lives. In this case the coating only represented a 4% increase in cross-sectional area, and, based on extrapolation of strength levels of similar coating compositions [3], it was probably very weak.

Since TBC coated superalloys can significantly improve the use temperature of these materials in high stress-aggressive environmental conditions, such as those found in gas turbine engines [4–35], the influence of the TBC coating on overall strength could be an important design consideration. To this end both bare and TBC coated AE 437A Ni base superalloy samples were stress rupture tested between 600 and 850 °C with particular emphasis given to 800 °C testing leading to lives on the order of 10,000 h. This substrate material was chosen for study since it is mostly employed for manufacturing compressor and stationary stator blades in aero turbines [35,36].

2. Experimental

2.1. Superalloy

Hot rolled Ni base superalloy grade AE 437A (Table 1) which had been solution treated and aged (1080 °C for 8 h; air cooled; aged at 700 °C for 16 h; air cooled) was the alloy selected for testing. This heat treatment schedule yielded a non-textured γ'-strengthened polycrystalline alloy with ~60 μm diameter grains containing intragranular as well as intergranular carbides. A more complete description of the heat-treated microstructure can be found in [35].

2.2. Test specimen

The specimen geometry was maintained as flat specimen (dog bone shape) with nominal dimensions of a thickness of 3 mm and a width of 4 mm with a 35 mm gage length, which was parallel to the longitudinal direction of the bars of AE 437A Ni base superalloy. The specimens were machined by electrical discharged machining (edm) and either tested with this as-edm'ed surface finish (bare

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doi:10.1016/j.msea.2009.01.033

Table 1
Chemical analysis of the substrate.

Material	Elements (wt.%)											
	Cr	Si	Mn	Ti	Al	C	Fe	Ce	P	S	Pb	Ni
AE 437A	19.82	0.06	0.19	2.50	0.81	0.039	0.07	0.01	0.003	0.001	0.001	Balance

specimens) or subjected to coating and then tested (TBC coated specimens).

2.3. Generation of TBCs

A Ni–20Co–18Cr–12.5Al–0.6Y (nominal composition in wt.%) type metallic undercoat/bond coat was first applied by plasma spraying to ensure the bonding and adherence of the top coat ceramic layer to the substrate and also to improve the environmental resistance of the TBC system. Thereafter, a zirconia (stabilized with 8 wt.% yttria) based top coat was plasma sprayed on the bond coat. The plasma gas for the TBC as well as for the bond coat was a mixture of Ar/H_2. Further details regarding the plasma spraying can be found in [35]. The bond coat and ceramic top layer were deposited by plasma spraying on all the four sides of the flat, solution aged and machined specimens. Optical metallography of the TBC coated stress rupture specimens revealed that the ceramic top layer and the bond coat were ∼295 and ∼100 μm thick, respectively (Fig. 1(a)).

2.4. Stress rupture tests

Stress rupture tests on the TBC coated (substrate + bond coat + top coat) and uncoated (bare substrate) specimens were undertaken per the ASTM 139/83 specification in air on constant load Mayes creep testing machines at 800 °C at stresses ranging from 100 to 50 MPa to give lives between 1000 and 10,000 h. Additional single point testing was conducted on TBC and bare samples at 50 °C intervals from 600 to 850 °C at high stresses to give lives between 100 and 1000 h. The engineering stress on TBC specimens was based solely on the cross-sectional area of the superalloy substrate, as it was presumed that neither the bond coat nor ceramic top coat would contribute to the load bearing capacity of the TBC coated superalloy samples. The test temperature was monitored by Pt–Rd type thermocouples, tied at the gauge length portion of the specimen. The temperature was controlled within ±2 °C of the set temperature. All testing commenced after a 1 h soak to ensure that the specimen attained the required temperature.

3. Results and discussion

The stress rupture results, including failure time, tensile elongation and reduction in area at the failure location, for bare and TBC coated AE 437A stress rupture specimens are listed in Table 2 as functions of test temperature and engineering stress. Overall the failure ductility is low, ranging from ∼5 to ∼15%, where for identical testing conditions the ductilities are quite similar for both the bare and TBC coated samples. Furthermore the near equivalence between the elongation and reduction in area values for each tested sample indicates that creep deformation was probably uniform, as little evidence for necking exists.

The time to failure data are graphically presented in Fig. 2, where part (a) illustrates the 800 °C results in a traditional logarithm life versus logarithm stress format and part (b) gives all the test values in the form of Larson Miller Parameter as a function of stress with LMP defined by

$$\mathrm{LMP} = T(15 + \log(t_r)), \quad (1)$$

where T is the absolute temperature in Kelvin and t_r is the rupture time in hours. The 800 °C data Fig. 2(a) and Table 2 indicate that at higher stresses the TBC coated alloy exhibits longer lives than the bare material and such an advantage, as reflected by larger LMP values in Fig. 2(b) and Table 2, exists at other temperatures. However the lower stress 800 °C results in both Fig. 2(a and b) and Table 2 clearly indicate that this superiority is lost for prolonged test lives.

The curves in Fig. 2(a) represent linear regression fits of the 800 °C time to rupture data to the usual power law equation

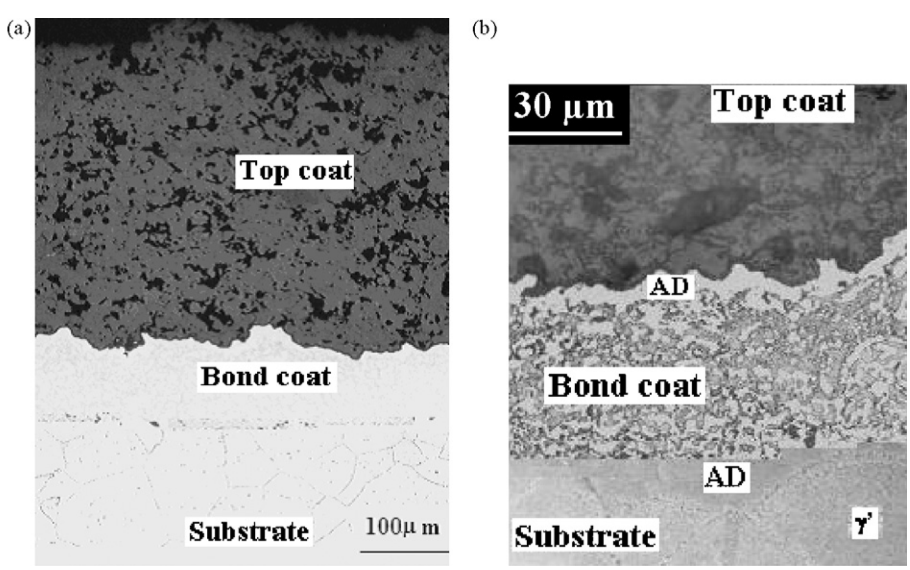

Fig. 1. Cross-sections of AE 437A/bond coat/top coat region of TBC coated test specimens (a) as coated [35], and (b) along the gage length, away from the fracture site, after testing for 13,000 h at 800 °C—50 MPa to failure, where AD indicates Al-depleted regions [36].

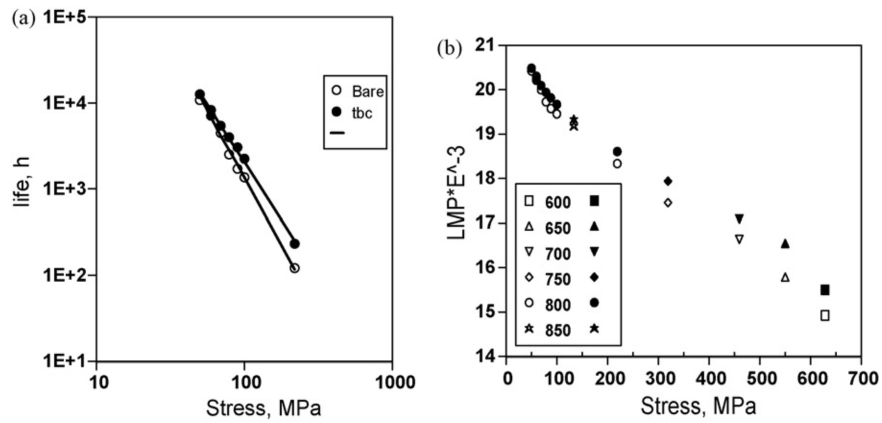

Fig. 2. Time to rupture of bare and TBC coated AE 437A as a function of (a) engineering stress at 800 °C and (b) Larson Miller Parameter for testing between 600 and 850 °C. Open symbols represent results from the bare superalloy while filled symbols correspond to TBC coated material.

(Eq. (2)),

$$t_r = A\sigma^p \tag{2}$$

where A is a constant in hours, σ is the stress in MPa and p is the stress exponent. The results of the fits are given in Table 3 with δ_p being the standard deviation for the stress exponent and R_d^2 is the coefficient of determination for the fit. Clearly from Fig. 2(a) and Table 3 both material conditions can be well described using Eq. (2).

Following Ray et al. [16], a significant portion of the Larson Miller Parameter data can be described using Eq. (3), where

$$\mathrm{LMP} = B + C(\log\sigma), \tag{3}$$

where B and C are constants. The curves resulting from this fit are shown in Fig. 3 and the values for these constants and the standard deviation for C, δ_C, and the coefficients of determination for the fits are given in Table 3. Because of the tailing off of the high stress results, the fitting of both material conditions was restricted to stress values less than 500 MPa, and as is indicated in Fig. 3 and by the regression coefficients in Table 3(b), use of Eq. (3) can describe the data adequately.

Of most importance in all the representations of the stress rupture results (Figs. 2 and 3) is the observation than any apparent strengthening of the TBC coated AE 437A samples over the bare superalloy is lost as temperature and/or rupture life are increased. It is probable that the initial strength advantage for the TBC coated material is the result of the bond coat bearing some load under the

Table 2
Stress rupture life of air tested bare and TBC coated AE 437A as functions of engineering stress and temperature.

Temperature (°C)	Stress (MPa)	Life (h)	Elongation (%)	Reduction in area (%)
(a) Bare				
600	630	139.1	15	16
650	550	130.3	10	11
700	460	126.7	10	11
750	320	118.9	8	9
850	135	123.9	10	9.5
800	220	122.8	10	10
800	100	1,412	14	16
800	90	1,776	7.5	9
800	80	2,578	8	7
800	70	4,488	4	7
800	60	8,328	5	8
800	60	7,284	7	9
800	50	11,000	8.5	9
(b) TBC coated				
600	630	610.7	13	15
650	550	907.3	10	10
700	460	375.4	9.4	10
750	320	357.5	9	9
850	135	166.6	9	8.8
800	220	232.9	9	8.1
800	100	2,268	13	14.5
800	90	3,120	6.5	8.4
800	80	4,028	7.8	6.7
800	70	5,600	5	6.5
800	60	7,200	7.2	7.4
800	60	8,500	8.1	9
800	50	13,000	8.8	9

Table 3
Linear regression fits for air tested bare and TBC coated AE 437A: (a) The time to rupture results as a function of engineering stress at 800 °C and (b) Larsen Miller Parameter as a function of engineering stress.

Condition	A	p	δ_p	R_d^2
(a)				
Bare	2.48E+009	−3.12	0.087	0.995
TBC coated	5.03E+008	−2.69	0.075	0.995
Condition	**B**	**C**	**δ_C**	**R_d^2**
(b)				
Bare	2.71E+004	−3843	151	0.986
TBC coated	2.64E+004	−3377	142	0.984

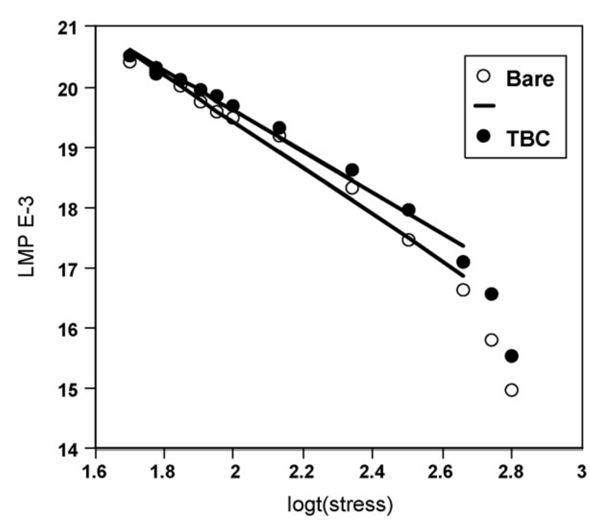

Fig. 3. Larsen Miller Parameter as a function of base 10 logarithm of engineering stress for air tested bare and TBC coated AE 437A. Open symbols represent results from the bare superalloy while filled symbols correspond to TBC coated material.

high stress/lower temperature exposure conditions, as suggested by [1]. Based on cross-section, a 100 μm thick bond coat on a 3 mm by 5 mm sample cross-section, the potential load bearing area would be increased by ∼10%, and the current bond coat composition of Ni–20Co–18Cr–12.5Al–0.6Y falls in the range of Ni base superalloys and would be strengthened by γ′-precipitates. [3].

While helpful under the higher stress/lower temperature exposure, the load carrying capacity of the bond coat appears to be diminishing for lower stress, longer term, higher temperature conditions as the properties of bare and TBC-coated specimens converge (Figs. 2 and 3). This tendency is also the case TBC coated Superni C263 [1], where the coated and bare alloy have similar strengths for LMP > 19,000 while the coated material is stronger at lower LMP values. The loss of strengthening is likely due to interdiffusion between the substrate and bond coating as well as the thermally grown oxide layer formed between the bond coat and top coat (Fig. 1(b)). Both interdiffusion between the bond coat and substrate and thermally grown oxide would reduce thickness of the bond coat and its Al level (Fig. 1(a)) which in turn would lower the γ′ content of this region and its strength. In reality, interdiffusion between a bond coat and its substrate can produce significant microstructural instabilities, which could have dramatic effects on overall strength, for example see [37]. This study confirms that TBC coated superalloys can possess a rupture strength advantage over uncoated material under shorter term, lower temperature conditions (smaller LMP values); however for longer term, higher temperature exposure this advantage is lost. In the present case of TBC coated AE 437A with a relatively thick initial Ni–20Co–18Cr–12.5Al–0.6Y bond coat, the 800 °C strength levels of the coated and bare material converge (Table 2, Figs. 2 and 3) for conditions yielding lives of 5000 to 10,000 h. Thus, for 800 °C design purposes, a TBC coated AE 437A part should have rupture properties at least equivalent to the bare superalloy up to 10,000 h. Extrapolation of the existing stress rupture/LMP data (Figs. 2 and 3) suggest that this equivalence is not maintained for longer lives and the TBC coated alloy would be weaker, but until testing is conducted at lower stress levels, lesser life for TBC coated material is only a contention.

4. Conclusions

Based on a study of the 600–850 °C stress rupture properties of bare and TBC coated AE 437A superalloy, where the ∼100 μm thick bond coat increased the cross-sectional area by about 10%, the shorter term, higher stress lives for the TBC coated alloy were greater than those for the unprotected material. This strengthening is believed to be due to load bearing by the bond coat; however under lower stress and subsequent longer lives, there was little difference in the times to failure between either bare or coated material, as the bond coat could no longer support significant loading.

Acknowledgements

The authors are grateful to Professor S.P. Mehrotra, Director NML (CSIR) Jamshedpur, India for his kind permission to publish this manuscript and to DMRL Hyderabad, India for generating the coatings.

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