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Effect of Bond Coating Surface Morphology on the TBC System Lifetime

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Abstract

A study on the effect of bond coating (BC) surface modifications prior to ceramic deposition is presented. Grit blasting and polishing were used to modify the BC surface finish. Thermal barrier coating (TBC) systems were made of a commercial yttria-stabilized zirconia (YSZ) deposited by electron beam physical vapor deposition on a β -(Ni,Pt)Al-coated Ni-based single crystal superalloy. Surface roughness measurements and scanning electron microscopy observations, before and after thermal cycling at 1100 °C, were performed to investigate the influence of the initial surface treatment on the YSZ/BC interface morphology and top coat spallation resistance. Surface states enhancing TBC spallation resistance have been found. In particular, it is shown that rumpling can be avoided even in the presence of phase transformations in the BC, by grinding samples with P600 SiC paper or by applying an “heavy” grit blasting leading to a thinner BC.

Keywords Pt-modified nickel aluminide · Surface roughness · High temperature oxidation · Grit blasting · Surface treatment · TBC

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Introduction

Thermal barrier coating (TBC) systems are used in aeronautic gas turbines to allow a higher combustion temperature or to increase the lifetime. The multi-layer system studied here consists of a Ni-based superalloy coated with an Al-enriched bond coating (BC) on which an yttria-stabilized zirconia (YSZ) topcoat (TC) is deposited by electron beam physical vapor deposition (EB-PVD). In case of β -(Ni,Pt)Al BC and EBPVD YSZ TC, failure of TBC systems occurs generally by spallation of the ceramic layer at the BC/TC interface, where a thermally grown oxide (TGO) made of alumina has grown. In case of an adherent system, *i.e.*, for long life (hundreds of 1 h cycles at 1100 °C or more), the damage mode is usually attributed to “rumpling” (also called “ratcheting”) of the β nickel aluminide BC. Rumpling is influenced by several factors, as reported in the literature: (i) the mismatch of the coefficients of thermal expansion between the superalloy and the bond coating, (ii) the mismatch of the coefficients of thermal expansion between the bond coating and the alumina scale which leads to large compressive stresses of several GPa in the alumina scale after cooling [1–3]. Xie et al. [4] demonstrated that grit blasting the BC decreases the compressive stress in the TGO by 1 to 2 GPa compared to as-aluminized samples cooled from 1100 °C to room temperature, (iii) the morphological instability of the TGO under compressive stresses enhanced by initial defects [1, 5–7]; (iv) the creep of the BC [1, 3, 7]; (v) the martensitic transformation of the β -NiAl phase [5, 6, 8]; (vi) the phase transformation β -(Ni,Pt)Al \rightarrow γ' -(Ni,Pt)₃Al which occurs in the BC because of aluminum consumption [9]. Vialas et al. [10] pointed out that the composition of the phases and the localization of the phase transformation need to be taken into account in order to calculate the volume change associated with this transformation.

Tolpygo et al. revealed that rumpling increases under thermal cyclic oxidation compared to isothermal oxidation. A rise of 100 °C (1100 °C to 1200 °C) increases rumpling by a factor of 4 after 100 cycles under cyclic oxidation [11]. Rumpling is also sensitive to cycling frequency [11, 12]. The presence of the ceramic topcoat decreases significantly the rumpling [2, 13]. Indeed, it was shown that the roughness parameter R_q can be reduced by a factor 2 when applying a ceramic topcoat, after cycling at 1150 °C [2].

Surface modifications of β -(Ni,Pt)Al bond coats play a major role in TC spallation resistance. Vaidyanathan et al. [14] or Xie et al. [4] showed that the lifetime of TBC systems can vary by a factor of 10 for non-grit-blasted bond coatings. Polishing samples seems to be a way for enhancing TBC spallation resistance. Gell et al. [15] obtained an increase by a factor 3 by polishing down to 1 μ m diamond paste. Spitsberg et al. [1], Yanar et al. [13, 16] and Jackson et al. [13, 16] found a gain ranging between 2 and 4 in TBC lifetime by polishing samples. Nevertheless, it was shown that the surface should not be so smooth that it results in the development of less strain-tolerant dense TC ceramic [13].

Many studies have been published already on the understanding of the roots of rumpling which is responsible for early TBC spallation during high temperature

exposure. This study brings new data on commercial TBC systems. It focuses on the effect of surface morphology before EB-PVD deposits, on TBC spallation resistance in thermal cycling test at 1100 °C.

Experimental Procedures

Materials

Experiments were conducted on disk-shaped samples of 25 mm in diameter and 2 mm thickness. They were composed of a β -(Ni,Pt)Al bond coating grown on an old version of Ni-based first generation superalloy single crystal substrate (AM1) with the following composition in wt%: 5.3Al-7.5Cr-6.5Co-2Mo-5.5W-8Ta-1.2Ti and 0.22 ppm S. The aluminide bond coating formation process was carried out in two steps. First, a layer of 7 μ m of Pt was electro-deposited. Secondly, the samples were aluminized by a low activity chemical vapor deposition process. This led to the formation of a single-phased β -(Ni,Pt)Al bond coating with a thickness close to 60 μ m.

This work reports the effects of two types of surface modification processes prior ceramic deposition. The grit blasting treatment, which is the current industrial process, was chosen to study the sensibility of TBC spallation resistance to grit blasting parameters. The grinding/polishing was also chosen to verify if this technic implies higher lifetimes, as reported in the literature for several bond coating/superalloy systems [1, 2, 13, 16].

The topcoats made of YSZ were deposited using EB-PVD at CCC (Ceramic Coating Center, Chatellerault, France), with a thickness of 150 μ m, and this ceramic layer presented a standard columnar structure.

Surface Treatments

After forming the β -(Ni,Pt)Al coating, but before depositing the ceramic layer, samples were subjected to several surface treatments. Varying grit blasting parameters and different grinding and polishing processes were applied to produce the samples for this study. In total, 6 different series of 5 samples were prepared: 4 series by grit blasting process and 2 by polishing/grinding process. Each series is identified and described below:

- “*Reference*”: The BC received a typical grit blasting treatment used in the industry
- “*Very light grit blasting*”: Lower pressure and shorter duration than the reference were applied
- “*Light grit blasting*”: Samples were grit blasted at lower pressure but with a longer time of exposure
- “*Heavy grit blasting*”: Higher pressure and shorter exposure duration were applied

- “*Light polishing*”: Specimens were partially polished with 3 μm diamond paste
- “*Grinding*”: Samples were ground to P600 SiC paper.

The average size of the corundum particles used for grit blasting was always the same and about 70 μm in diameter. Polishing samples with 3 μm diamond paste was used only to decrease the height of the BC grain boundary ridges. For grinding trials, samples were scratched on SiC paper until the whole surface was ground and care was taken in order to remove a minimum thickness of the BC. The synopsis of the experiments can be seen in Fig. 1a. Three samples of each series were used for thermal cycling tests, one for SEM and EDX investigations in as-treated condition, and one without TBC for surface roughness measurements.

Cyclic Oxidation

All samples were subjected to thermal cycling in laboratory air. Each cycle consisted of a 15 min heat up to 1100 $^{\circ}\text{C}$ and a 45 min hold at 1100 $^{\circ}\text{C}$ followed by

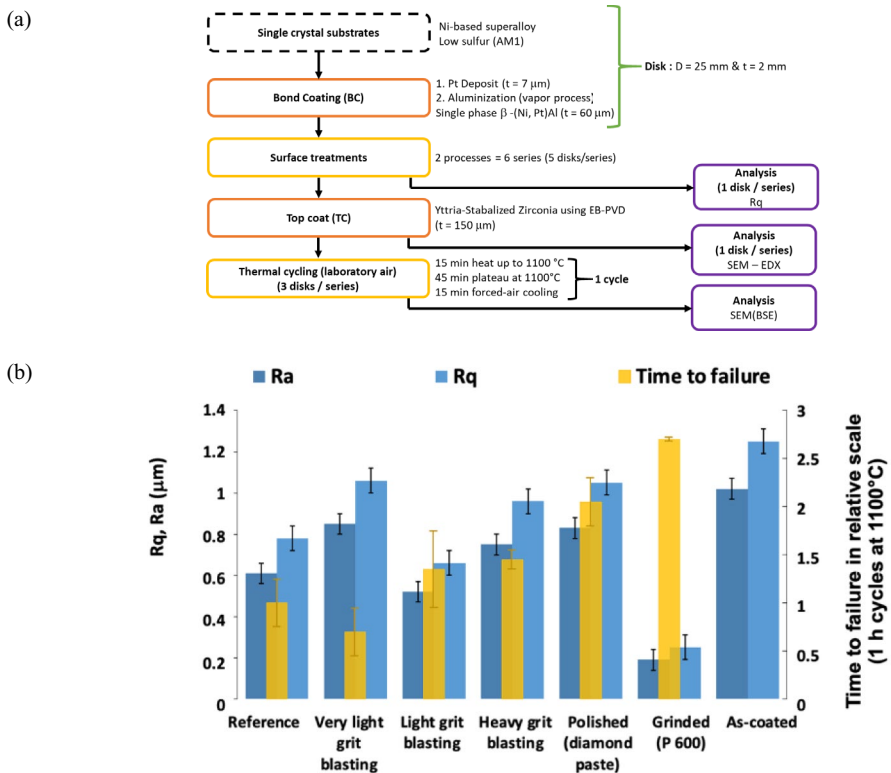


Fig. 1 a Synopsis of the experimental plan b Surface roughness of β -(Ni,Pt)Al bond coating after surface treatments, as measured by optical interferometry and influence of surface treatments on lifetime of TBC systems (thermal cycling at 1100 $^{\circ}\text{C}$ in laboratory air—1 h cycles)

a 15 min forced-air cooling to room temperature. Samples were cycled until 50% of the surface of the ceramic layer failed. This percentage of topcoat spalling was used to define the lifetime of TBC systems. The fracture surfaces were examined using a Philips XL40 FEG scanning electron microscope. Energy-dispersive X-ray spectroscopy measurements were realized with an EDAX system to analyze the chemical composition of the BC. A Zygo NewView 100 interferometer system was used to measure the roughness of the samples after the surface treatments.

Results and Discussion

SEM Investigations and Surface Roughness Measurements

Figure 1b gives the results of surface roughness parameters R_a and R_q as a function of surface treatments. R_a is the average of the deviations from the main line, whereas R_q considers the squared deviations from the mean line. Therefore, R_q gives more importance to the largest deviations, such as the ridges here. In the as-aluminized condition, roughness parameter R_q is equal to $1.25 \pm 0.07 \mu\text{m}$. Reference samples show a lower value of roughness parameter R_q of $0.78 \pm 0.08 \mu\text{m}$. SEM investigations of the cross sections at the BC/topcoat interfaces, after the different surface treatments, are shown in Fig. 2. Concerning the reference state, the grain boundary ridges are no longer observed at bond coating/topcoat interface. In the cross sections (Fig. 2), black particles (with backscattered electrons) are visible in the BC/interdiffusion zone area. These particles are grit-blasting corundum grains, resulting from the blasting of the superalloy prior to Pt electroplating. Additionally, smaller particles, originating from the BC grit blasting, are sometimes observed near the BC surface. A higher surface roughness value ($R_q = 1.06 \pm 0.05 \mu\text{m}$) compared to the reference samples is obtained by applying a very light grit blasting to the BC (Fig. 1b). The SEM images show that the microstructure present after aluminization remains visible. The light grit blasting samples exhibited a kind of micro-roughness which is homogeneous all along the interface (Fig. 2). The lowest value of R_q using the grit blasting process is obtained for this case with $R_q = 0.66 \pm 0.07 \mu\text{m}$. This condition gives a surface free of bond coating grain boundary ridges. With a heavy grit blasting, the coating thickness was reduced by a factor 2 (Fig. 2). But surprisingly, the roughness of this surface increased only slightly ($R_q = 0.97 \pm 0.07 \mu\text{m}$) in comparison with the reference (Fig. 1b).

These results indicate that increasing the pressure and exposure time of grit blasting process results mainly in decreasing the BC thickness without increasing too much the surface roughness measured in terms of R_a or R_q . Nevertheless, the coating surface appeared more damaged and the surface irregularities lead to defects in the EB-PVD zirconia topcoat as seen on cross section (Fig. 2). The partially polished samples exhibit a surface roughness parameter R_q about 20% lower than the as-aluminized samples ($1.05 \pm 0.11 \mu\text{m}$ and $1.25 \pm 0.07 \mu\text{m}$, respectively). Compared to the “as-coated” samples, this surface treatment reduces the height of the ridges at grain boundaries. The cross sections show that the surface state is smooth with some imperfections corresponding to the grain boundaries (Fig. 2). The

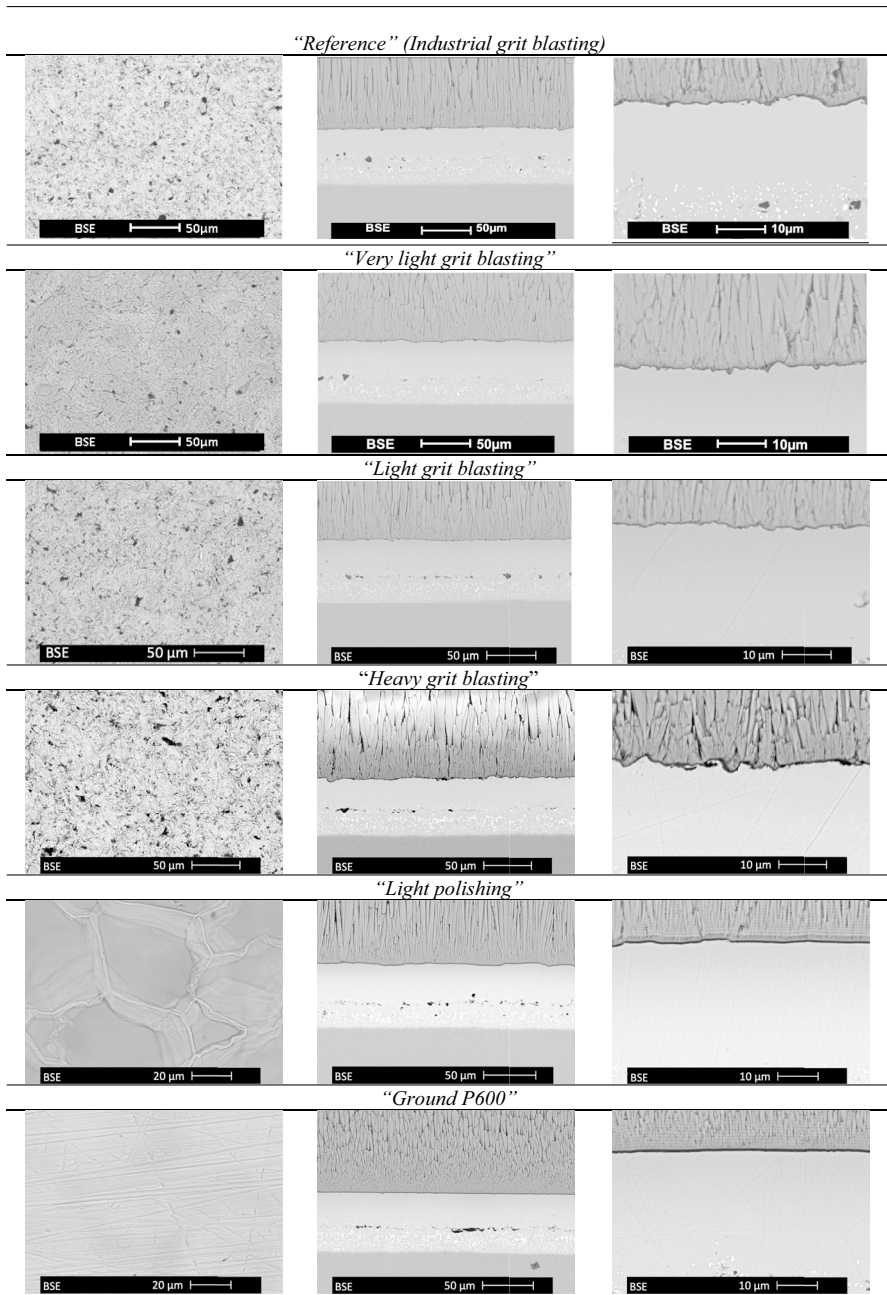


Fig. 2 SEM investigations of the cross sections at the BC/topcoat interface. First column: BC surface. 2nd and 3rd columns: cross sections with two different magnifications

smoothest surface state is obtained with ground samples, with a R_q parameter equal to $0.26 \pm 0.05 \mu\text{m}$. The SEM image confirms this smooth surface state which allows the TBC to grow free of defects. Focusing on the alumina scale, we can observe that the TGO grown during the EB-PVD process is thicker on a ground surface than on grit-blasted samples.

Thermal Cycling Results

Thermal cycling tests were performed at 1100 °C on samples with different surface state morphologies. 3 samples for each surface treatment were tested, and the results are presented in Fig. 1b. They show the average lifetime of the 3 samples and the standard deviation. Reference samples have given the reference lifetime level of 1. This lifetime, when expressed in number of cycles, is in agreement with the expected results from our previous laboratory experience on the same systems. The lowest TBC lifetime is found for samples with a “very light” grit blasting. Two groups of samples present an increase of about 40% in TBC spallation resistance. These samples result from “light grit blasting” and “heavy grit blasting” processes. They exhibit an interesting “micro-roughness” and a “thinner coating” character, respectively. Reducing the height of grain boundary ridges by a partial polishing with a 3 μm diamond paste increases the TBC spallation resistance by a factor of 2. Finally, the best results are obtained by grinding the samples which gives a lifetime enhanced by a factor of 2.7 when compared to the reference.

SEM investigations, shown in Fig. 3, were performed after the thermal cycling at the BC/TC interface.

Reference Bond Coatings

SEM investigations reveal many undulations of the BC even in the presence of the ceramic topcoat (Fig. 3). The spallation occurs at the ceramic TC/TGO interface, and the TGO remains always adherent to the BC.

Very Light Grit-Blasted Bond Coatings (Lower Pressure, Shorter Duration)

Soft grit-blasted samples present a lower resistance to spallation during thermal cycling. These results can be linked to their microstructure. Figure 3 shows that the grit blasting process has modified the surface morphology but not enough to totally delete the initial microstructure formed during aluminizing (i.e., bond coating grain boundary ridges are still present). Interferometer profiles confirm this microstructure, as shown in Fig. 4. This surface morphology which is close to the as-aluminized microstructure allows cracks initiations at the ridges and leads to spallation of the ceramic topcoat. The wide range in lifetimes could then be related to the distributions of grain sizes and to the radius of curvature and height of the bond coat ridges [14].

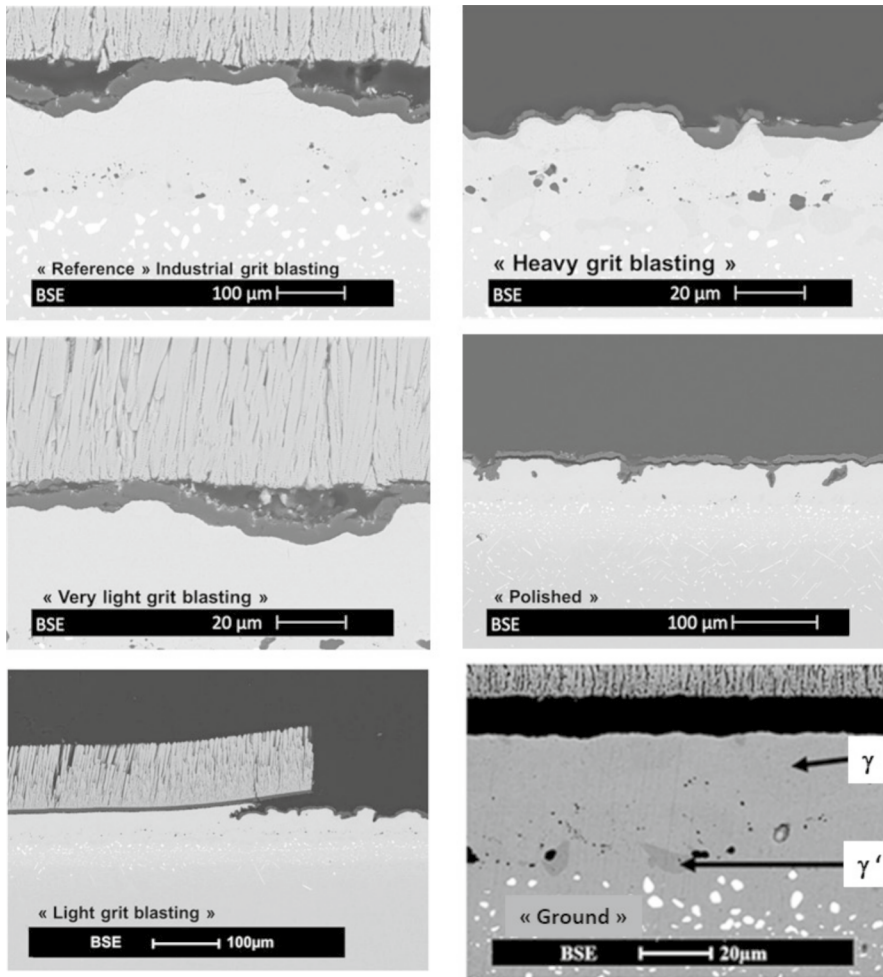


Fig. 3 Cross section SEM investigations after thermal cycling at 1100 °C in laboratory air—1 h cycles

Light Grit-Blasted Bond Coatings (Lower Pressure, Longer Duration)

Well-defined grit blasting parameters permit to obtain bond coatings with a very regular surface without ridges at bond coating grain boundaries. The as-aluminized surface microstructure is totally deleted. The BC/topcoat interface appears relatively smooth, and a “micro-roughness” is created (Fig. 3). Roughness measurements give the lowest value of R_q compared to all other grit-blasted samples. With this surface state morphology, TBC lifetime increases of about 30% in thermal cycling test when compared to reference samples. This increase can be attributed to the smoothness of the surface which minimizes the defects at the BC/topcoat interface. The SEM investigations show also that the BC surface experiences very little plastic strain

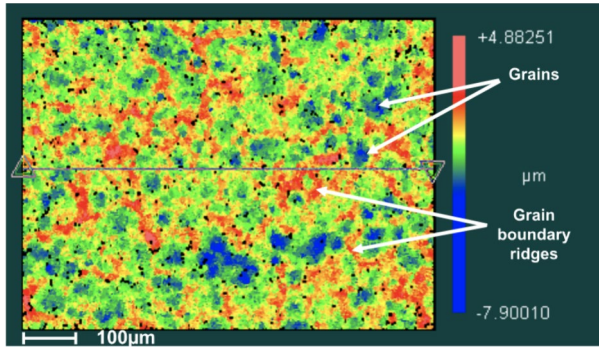


Fig. 4 Profilometer scan of a “Very light grit blasting” sample

where the ceramic layer is still adherent. The ceramic topcoat which has a low creep rate at 1100 °C constrains the bond coating strains appearing during thermal cycling tests (Fig. 3). SEM investigations show clearly that where the ceramic topcoat has spalled off, the BC surface is free to rumple in order to relax the elastic stress of the TGO/BC system through creep. The fact that alumina with small grains can creep in these conditions is well known, e.g., [16].

Heavy Grit-Blasted Bond Coatings (Higher Pressure, Shorter Duration)

High pressure grit blasting process leads to a decrease of the thickness of the β -(Ni,Pt)Al bond coatings down to about 20 μm (Fig. 3). This leads to an increase in TBC lifetime of 50% compared to the reference state, which can only be attributed to a coating thickness effect. Indeed, on the one hand, the roughness ($R_q = 1 \mu\text{m}$) is close to that of the reference surface state, and on the other hand, TBC defects are present in these samples due to some irregularities in the interface (compared to the smooth interface obtained by polishing or soft grit blasting). The better behavior of the thinner coating could be explained by a faster transformation of the β -(Ni,Pt) Al BC to a γ -Ni/ γ' -Ni₃Al BC, as the reservoir in Al is lower for a thinner coating. Indeed, the Pt-rich γ/γ' bond coatings are known to experience less rumpling than the β bond coatings [17, 18]. These experiments show clearly the effect of the BC thickness on the lifetime of TBC systems.

Light Polished Bond Coatings

Reducing the height of the ridges by only 20% compared to the as-aluminized state leads to a significant enhancement of the lifetime of TBC systems. TBC spallation resistance increases by a factor of 2. During thermal cycling tests, failures occur mainly at the topcoat/TGO interface (Fig. 3). However, the TGO is not adherent all along the interface. The mechanism responsible for TBC spallation seems to be the rumpling of the BC. Reducing the height of the ridges

located at the grain boundaries does not change the mechanism of failure when compared to the reference state, but it delays the occurrence of failure.

Ground Bond Coatings

Ground samples offer the best resistance to TBC spallation. TBC lifetime in thermal cycling tests at 1100 °C is enhanced by a factor 2.7 compared to the reference. Indeed, SEM investigations presented in Fig. 3 show a very interesting behavior, indicating that the BC surface remains smooth after a great number of cycles at 1100 °C. The consequence of this very long lifetime is that the BC is fully transformed to γ' and γ phases. It is very important to notice that the phase transformations did not produce coating rumpling with ground samples. Figure 5 shows that localized phase transformation is not a sufficient condition for bond coating rumpling.

Figure 2 shows that the TBC grown on ground samples is free of defects, when compared to TBC grown on grit-blasted surfaces. These defects can act as crack initiation sites. Then, a smooth surface has three positive effects. Without grain boundary ridges, there is little or no stress concentration sites and this explains the good thermal cycling behavior of the ground samples in comparison with the soft grit blasting and light polished samples. The second effect of grinding is to have fewer defects in the ceramic topcoat knowing that these defects act as flaws. Third, the lack of initial undulations causes the main stress to remain parallel to the TGO/BC interface and also allows a better bonding between the YSZ and the flat TGO. As a consequence, the BC does not rumple and the lifetime is improved when compared to grit-blasted samples.

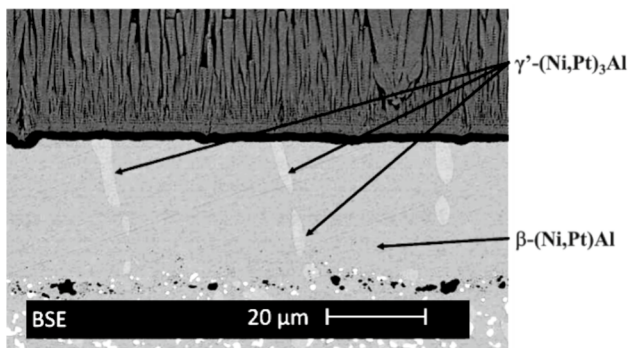


Fig. 5 SEM picture of localized β/γ' phase transformation inducing no rumpling after thermal cycles at 1100 °C on ground BC

Conclusions

Surface geometry of β -(Ni,Pt)Al bond coating has been modified prior to zirconia EB-PVD coating. Surface roughness measurements and SEM investigations have been performed on samples without ceramic topcoat in order to characterize the influence of grit blasting parameters, polishing and grinding treatments on surface roughness and morphology. Thermal cycling tests were performed to discriminate surface state morphology consequences on TBC spallation resistance. From this study, several conclusions can be drawn.

An industrial grit blasting leads to the decrease in roughness parameter R_q of 20% compared to the “as-coated” samples. A “**very light grit blasting**” ($R_q = 1.06 \pm 0.05 \mu\text{m}$) did not modify enough the surface state of the BC, the ridges located at BC grain boundaries are still present, and the surface morphology was closed to the as-aluminized state. A lower level than the reference in TBC lifetime was induced. A “**light grit blasting**” ($R_q = 0.66 \pm 0.07 \mu\text{m}$) with a BC surface free of grain boundary ridges and a regular micro-roughness was exhibited. A 30% increase in TBC lifetime was observed, permitting to confirm results from older studies [1, 4, 19] and more recent modeling [7].

A “**heavy grit blasting**” leads to R_q equal to $0.97 \pm 0.07 \mu\text{m}$, similar to lighter grit blasting. The TBC spallation resistance was extended by 50%, and this was attributed to the thinning of the BC down to $20 \mu\text{m}$ instead of $60 \mu\text{m}$ in the as-processed. A “**light polishing**” with $3 \mu\text{m}$ diamond paste ($R_q = 1.05 \pm 0.11 \mu\text{m}$) reduced the height of the ridges by only 20%. Nevertheless, the **time to failure** was multiplied **by a factor 2**. The same failure mechanisms were observed (rumpling), and the result confirmed the large negative effect of grain boundary ridges tips on thermal cycling resistance. A “**ground**” surface (SiC P600) **increases the lifetime by a factor of 2.7**. This was explained by a smooth and flat surface with no grain boundary ridges ($R_q = 0.26 \pm 0.05 \mu\text{m}$), which leads to the growth of an EB-PVD TBC with less defects and delays the initiation of rumpling.

Finally, the phase transformation β -(Ni,Pt)Al \rightarrow γ' -(Ni,Pt)₃Al occurring in the BC during high temperature exposure does not enhance the rumpling of the BC with ground samples. Thanks to the grinding, it appears clearly that this phase transformation is not the cause of the rumpling phenomenon in the present TBC system. On the contrary, a thinner bond coating resulting from grinding or from heavy grit blasting, leading to a Pt-rich γ/γ' bond coating microstructure after a shorter time than for thicker coatings, leads to a longer lifetime than the reference despite the presence of defects in the TC for the heavy grit blasting.

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Author contributions SH did the experimental work and the first draft of the manuscript, MD worked on the manuscript and figures, and DM reviewed the manuscript and discussed the experimental results + coordination.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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