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Pyramidal Structures on Yttria-Stabilized Zirconia after High Temperature Exposure at 1500°C: New Features on an Old Material

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ABSTRACT

For several decades, yttria-stabilized zirconia (YSZ) has been the state-of-the-art material for thermal barrier coatings (TBCs), e.g., in gas turbines, for temperatures up to 1200°C. At higher temperatures, the YSZ undergoes detrimental phase transformations and strong sintering, which leads to early failure of the TBC system. Recently, it was shown that this early failure is correlated to the exact cooling rate applied. It was shown that the lifetime of a TBC system tested in a burner rig at 1550°C was not reduced, when the cooling rates were reduced strongly, e.g., to 10 K/s. In the present study, a new, not yet in the literature reported, pyramidal topography was detected in YSZ samples being cycled at about 1550°C. Analyses were performed using scanning electron microscopy and also transmission electron microscopy. The pyramidal structures were present immediately after preparation of cross sections and increased in amount and size during storage at room temperature in laboratory air.

1 | Introduction

Thermal barrier coating (TBC) systems have been used for many decades to continuously improve and enhance the performance of hot section components, e.g., in modern gas turbines [1]. TBC systems reduce the temperature at the surface of the metallic turbine material, allowing either higher operating temperatures for the whole system or leading to longer lifetimes [2]. Many state-of-the-art ceramic topcoats for TBC systems are manufactured by means of atmospheric plasma spraying (APS). These ceramic topcoats, often made of yttria-stabilized zirconia (YSZ), consist of so-called splats from solidification, cracks due to thermal mismatch and quenching stresses [3], unmolten particles, and large porosity. With such a microstructure of cracks and pores, the effective thermal conductivity is strongly decreased [4].

The standard material YSZ has excellent properties for TBC applications as it has a low thermal conductivity, a high

toughness, a high thermal expansion coefficient, and phase and microstructural stability [5]. However, it has been stated in the literature for several decades that YSZ has a temperature limitation of about 1200°C for a long-term operation. At higher temperature, a degradation of the so-called t' phase sets in [6]. This phase is formed during the spray process due to the fast cooling and is a nonequilibrium phase. This tetragonal phase does not transform into monoclinic during cooling. At elevated temperatures, diffusion sets in and the high-temperature equilibrium phases, such as cubic and tetragonal, are formed. During cooling, the tetragonal phase will transform to monoclinic which can lead to cracking of the coating due to a large volume expansion. It is known that the amount of phase transformation considerably depends on the cooling rates, typically faster cooling suppresses the transformation [7]. However, if fast cooled samples are annealed at low temperatures, the transformation sets in according to Avrami–Johnson–Mehl–Kolmogorov kinetics [8].

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Another degradation mechanism is the sintering of the TBC at elevated temperature. The good thermal cyclic performance of TBCs is related to their microstructure, i.e., often a porous, microcracked microstructure is used which can tolerate stresses during cycling. At elevated temperatures, sintering sets in and the cracks and pores heal, leading to a stiff coating which will easily delaminate. Recently, it was found that YSZ TBCs can be used at much higher temperatures above 1500°C without detrimental phase changes [9]. The tests have been made in gradient testing in a burner rig similar to the condition in a gas turbine. At these high temperatures, the main driving forces for delamination are not the microstructural changes in the YSZ but the extremely fast cooling rates when the flame is removed due the strong radiative cooling. If the cooling rate is fixed to about 10 K/s by reducing the power of the gas burner, longer lifetimes compared to lower temperatures could be obtained. The constant cooling with about 10 K/s has to be extended to low temperatures below 100°C. This avoids the phase transformation from tetragonal to monoclinic [8]. These findings give the basis of the investigation presented here. We have observed a long lifetime in our TBCs cycled at surface temperatures above 1500°C and cooled with a cooling rate of about 10 K/s. In these samples, we observed a change at the surface after storage at room temperature. This is discussed here in detail.

2 | Results and Discussion

The image of the complete, cycled TBC system shows the three different layers, substrate, bond coat, and ceramic topcoat TBC (Figure 1a). Also, the alumina-based thermally grown oxide (TGO) at the interface between bond coat and topcoat is visible. The bond coat consists of γ -Ni phase and the aluminum-rich β -NiAl phase. Underneath the TGO, the bond coat exhibits a typical aluminum-depleted zone, as aluminum is consumed to form the TGO. Figure 1b shows the cross section of the topcoat in more detail. The typical microstructure of the ceramic top layer, consisting of cracks, pores, and splats, is prevailing. The upper part, where the specimen experiences the highest temperature, is denser compared to the middle and bottom layer.

In order to determine the grain size of the ceramic topcoat electron backscatter diffraction (EBSD), measurements were carried out to obtain the information of possible changes at the top, middle, and bottom region of the ceramic topcoat. For this purpose, only the cubic phase was proposed to the EBSD evaluation software. In Figure 2 (top row), the band contrast images, showing the pattern quality, are given. This type of images can be used to determine the grain size, as, e.g., on grain boundaries no pattern can be obtained, they will appear dark. In addition, regions where the pattern is disturbed, e.g., by dirt particles, scratches or other type of deformation will appear dark, too, as the signals

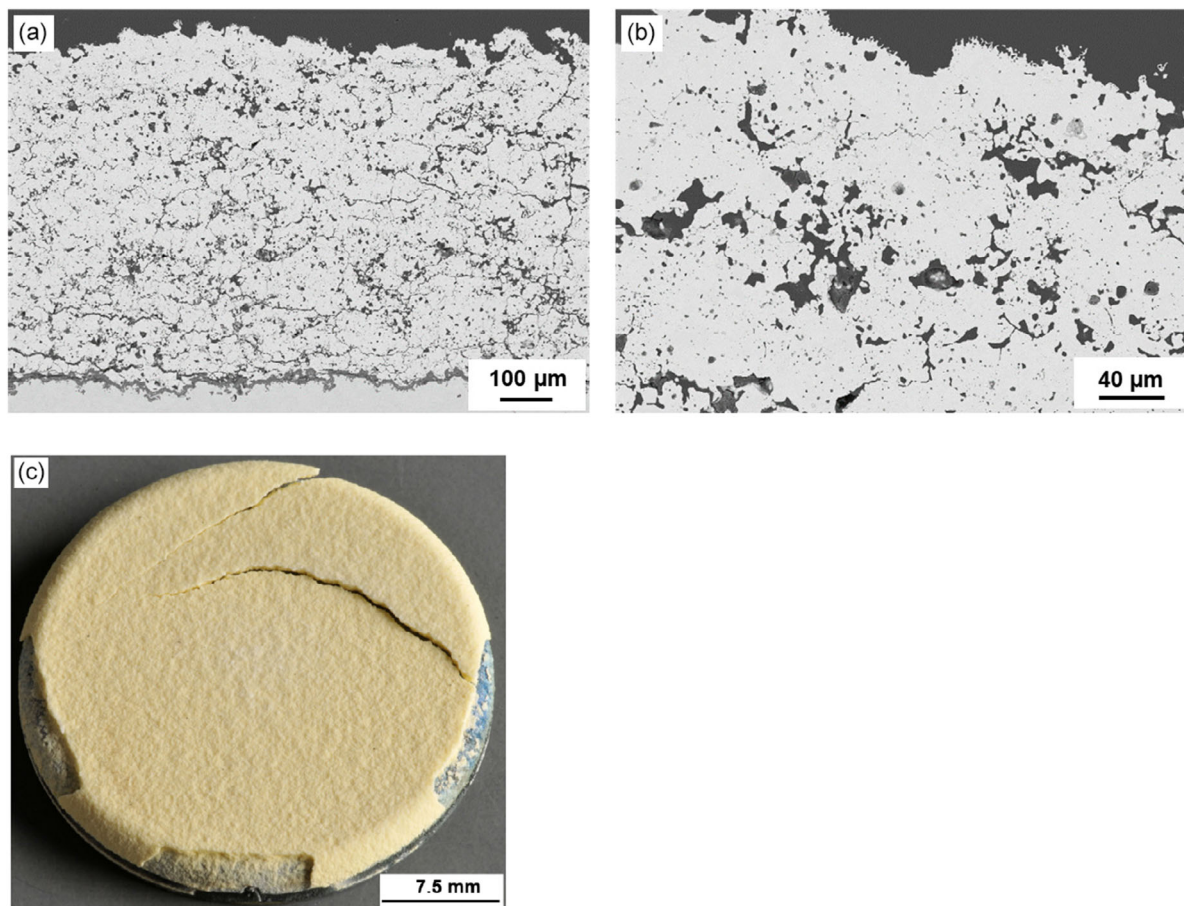


FIGURE 1 | BSE images taken of the cross section of TBC topcoat, (a) TGO and BC, (b) in more detail of the ceramic topcoat, (c) after burner rig test at 1554°C in air until failure and macroscopic image of the sample surface after failure. BSE = Backscattered electron; TBC = thermal barrier coating; TGO = thermally grown oxide.

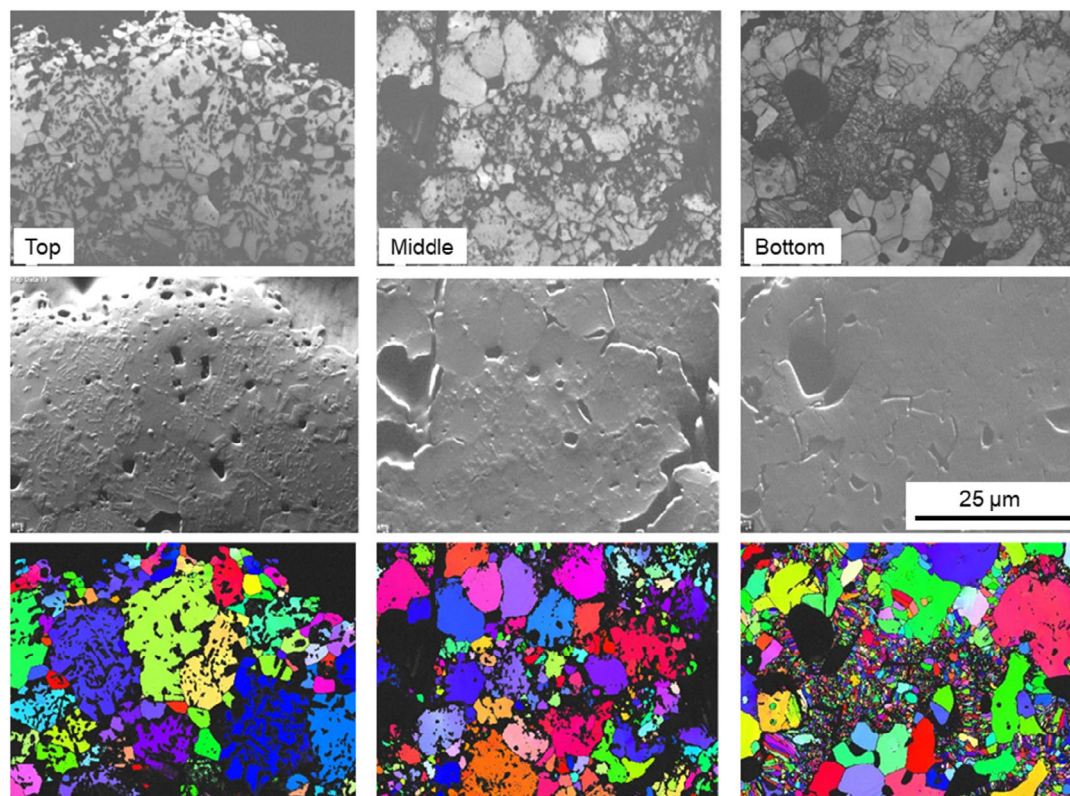


FIGURE 2 | Band contrast images (top row), forward scatter detector images (middle row), and IPFs in x -direction (lower row) of YSZ ceramic top part, middle part and bottom part after burner rig test at 1554°C in air until failure. YSZ = Yttria-stabilized zirconia.

for EBSD come from the outer top nanometers of the sample. Additionally, the images of the so-called forward scatter detector of the EBSD device are shown in Figure 2 (middle row). It is obvious that the top region of the ceramic topcoat consists of very large grains in the size of around 15 μm . This can be seen even more easily in Figure 2 (bottom row) in the colored inverse pole figures (IPFs) in the x -direction. Coming to the middle region the grain size decreases, and in the bottom region one can find a few larger grains combined with a large amount of very tiny grains (around 1 μm) which have a columnar shape, due to the fast solidification. Similar results have been observed in the literature showing fine grains in the as-sprayed condition and grain growth

during high-temperature treatment [10]. However, typically also larger amounts of fine-grained monoclinic phase are found in heat-treated samples [10].

A higher magnification of the top region, taken by the forward scatter detector, is shown in Figure 3, along with the corresponding IPF mapping. Here, protruding areas are visible, which can easily be assigned to the black (not identified) phases in the IPF mapping.

At this point, it was unclear why so many places besides grain boundaries and pores of the sample were not identified or had a very poor pattern quality. Therefore, in one place the EBSD analysis was carried out proposing the cubic modification as well as the monoclinic one (Figure 4). Indeed, in many places the

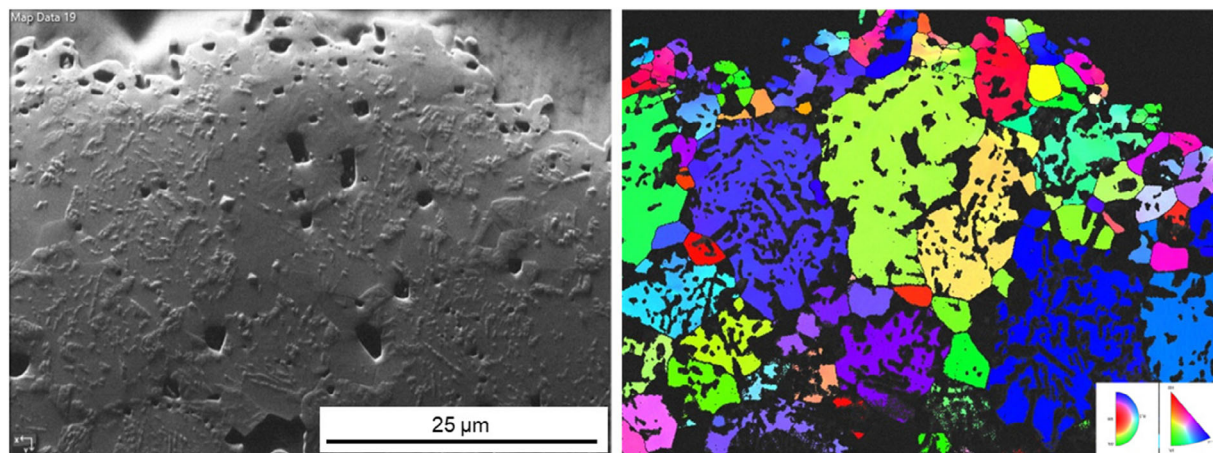


FIGURE 3 | Topographic image of the forward scatter detector and IPF in x -direction of YSZ after burner rig test at 1550°C in air until failure. IPF = Inverse pole figure; YSZ = yttria-stabilized zirconia.

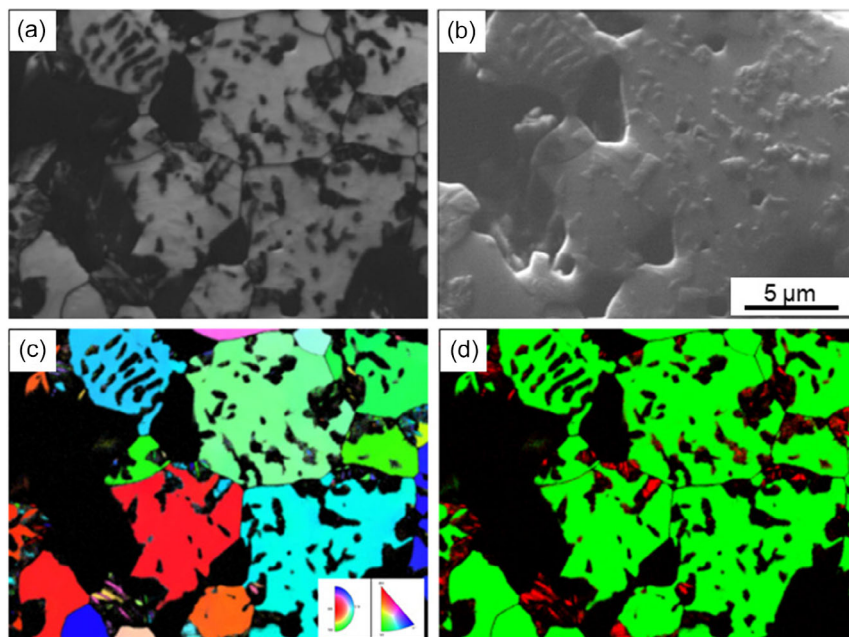


FIGURE 4 | (a) Band contrast image, (b) forward scatter detector image, (c) IPF in x-direction, and (d) phase map (green resembles the cubic and red the monoclinic modification) of YSZ after burner rig test at 1554°C in air until failure. YSZ = Ytria-stabilized zirconia.

monoclinic modification was found. However, it must be mentioned that not everywhere in the protruding areas the monoclinic phase was assigned by the evaluation software. In some cases, certain areas appear to have a weak or faded signal, or even none at all. At this point, the specific roughness, which was seen in the sample surface regions, was thought to be the reason for the lower pattern quality (which would result in weak and/or faded or no signals) and thereby reduces the recognition ability of the EBSD software.

With this in mind, the further scanning electron microscopy (SEM) study was carried out with the main focus on the cross-sectional surface features of the specimen. For the top region of the ceramic topcoat (Figure 5), a strong roughness (in the micrometer range) in some areas plus a relief type surface morphology is visible.

It should be mentioned that though in general being very dense due to sintering, some cracks are visible in the material and these cracks seem not to be originated from the APS process. On top of that, small variations of gray values are detectable in the

backscattered electron (BSE) images, indicating a change in chemical composition, which was corroborated by an energy-dispersive spectrometer (EDS) measurement (Figure 6). The elemental distribution of yttrium and zirconium is not homogeneously over the whole area, but in many locations, yttrium is strongly depleted. In the literature, the modulation of the yttrium content is known for heat-treated YSZ [6, 9]. A relief type surface morphology can be produced during polishing in cases when one phase is harder and more resistant than the other phase. In this case (compare Figure 5), mostly, the higher phases, which are sticking out or protruding, resembling the harder or more brittle composition, are the phases which were found to be depleted in yttrium. This behavior is not clear as it was reported that the zirconia with the lower amount of stabilizing agent showed the lower hardness [11].

In Figure 7, the surface morphology of the cross section and the phase distribution is given from the middle region of the topcoat. Again, phases, which are more brittle and additionally, are also depleted in yttrium, are detectable. However, in this middle

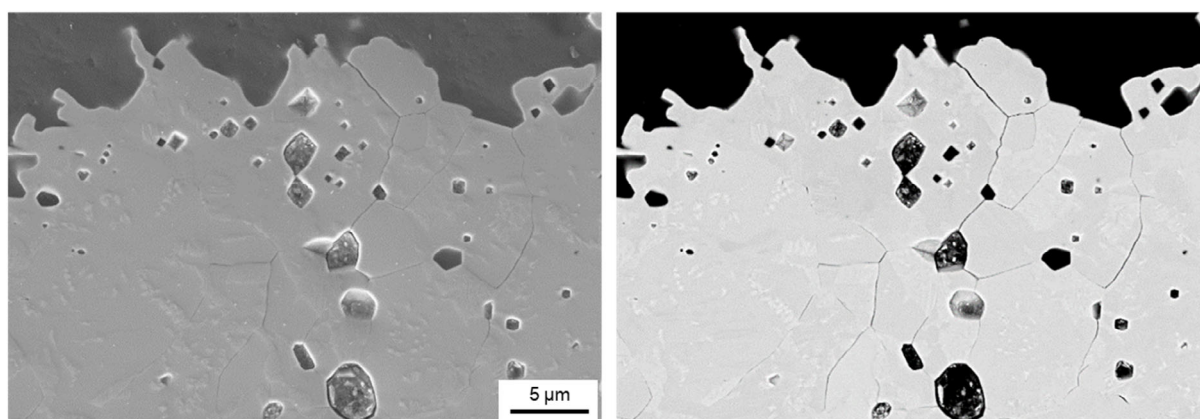


FIGURE 5 | SE image (left) and BSE image (right) of YSZ (top region) after burner rig test at 1554°C in air until failure. SE = Secondary electron; BSE = backscattered electron; YSZ = yttria-stabilized zirconia.

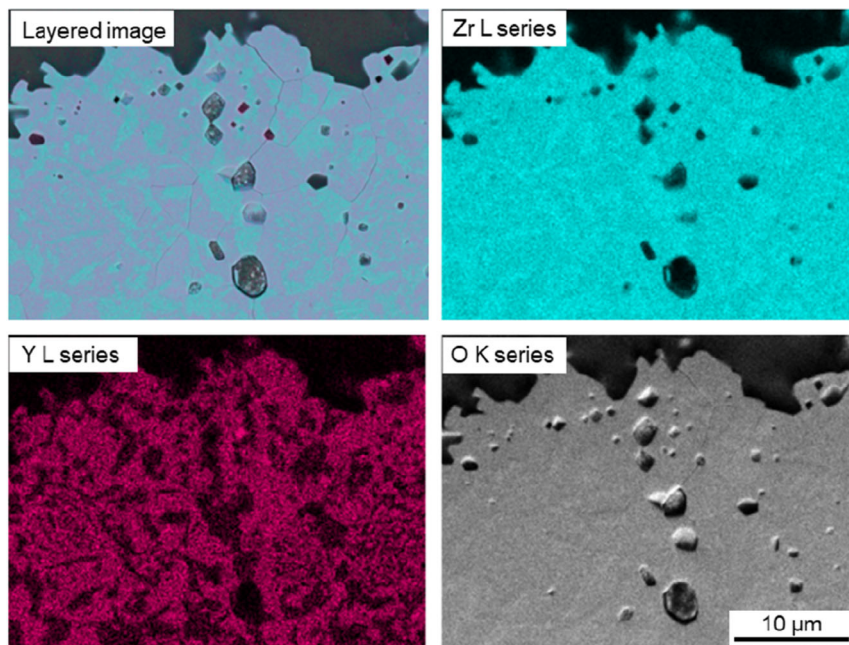


FIGURE 6 | EDS analysis of the TBC top region after burner rig test at 1554°C in air until failure, which is shown in Figure 5 plus layered image and elemental mapping of zirconium, yttrium, and oxygen. EDS = Energy-dispersive spectrometer; TBC = thermal barrier coating.

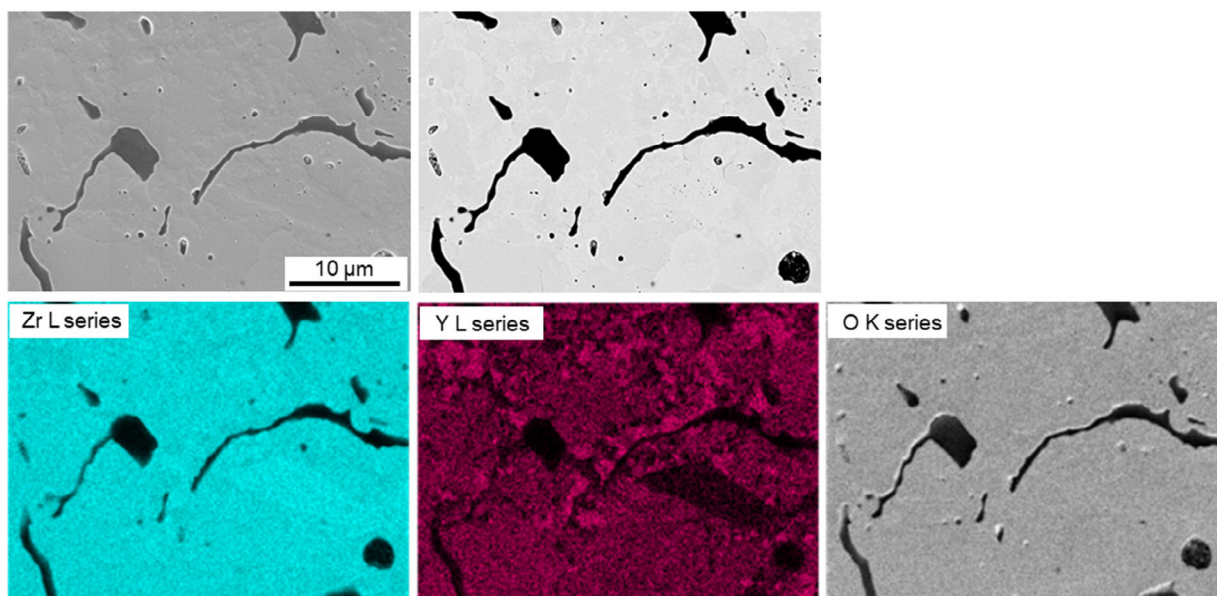


FIGURE 7 | SE and BSE images of YSZ after burner rig test at 1554°C in air until failure plus elemental distribution of zirconium, yttrium, and oxygen. SE = Secondary electron; BSE = backscattered electron; YSZ = yttria-stabilized zirconia.

region the effect of the discrete surface roughness has decreased. Interestingly, another phase enriched in yttrium is found, too.

In the bottom region of the ceramic topcoat, close to the interface TGO/bond coat, no depleted or enriched phases are detectable and no discrete roughness as well as no brittle/harder phases are found (not shown). This single-phase and nontopography region has a width of around 180 μm (not shown), it takes roughly one quarter of the total thickness of the topcoat.

The top region of the ceramic topcoat was investigated more intensely by SEM (Figure 8a–d) using higher magnifications. The focus was here on the discrete roughness in the micrometer

to submicrometer range, already mentioned before. As especially in this region, the EBSD results were not satisfying concerning the band contrast images and the phase detection. It is possible that, e.g., dirt or other disturbing artifacts might conceal the true surface. Nevertheless, the secondary electron images clearly reveal a new feature on the surface of the cross section in the form of square pyramids, having a square base and four triangles. The, from here on called, pyramidal structures are prevailing as singularities and sometimes they are arranged in strings (Figure 8c). These pyramidal structures can explain the bad detection in the EBSD analysis, because of the nonplanar

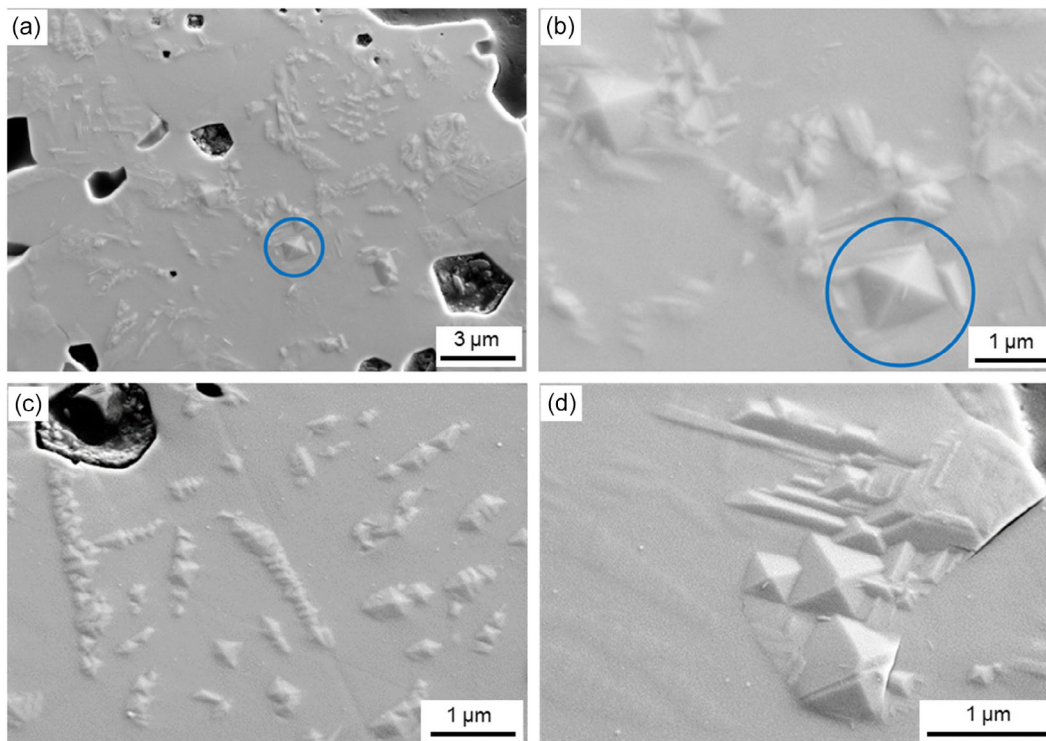


FIGURE 8 | SE images of YSZ (top region) after burner rig test at 1554°C in air until failure, (b) showing a higher magnification of the blue-marked region from (a), (c) arrangement of pyramidal structures in strings and (d) cracks next to pyramidal structures. SE = Secondary electron; YSZ = yttria-stabilized zirconia.

topography. Besides, in a few cases cracks were found next to them, too (Figure 8d).

As the sample is a metallographic cross section, it is clear that the protruding pyramidal structures must have grown after sample grinding and polishing. As the pyramidal structures were never seen before by the authors and also not reported in the literature concerning high-temperature applications of 8 wt. YSZ, they were checked by EDS. But due to their small size, even when using low accelerating voltages, there was never any indication that the new structures contained other elements, besides yttrium, zirconium, and oxygen. If the pyramidal structures are artifacts due to any contamination during the preparation process, one would expect finding typical elements such as C, N, S, P Na, Cl, K, or Ca. Admittedly, elements such as H cannot be detected by means of EDS, given still the possibility of hydrate formation or carbohydrates. Worth mentioning is though, that during EDS point analysis never a contamination burn spot or stain appeared as well as no evaporation or vanishing of the pyramidal structures. This is another strong hint that the pyramidal structures are no artifacts due to contamination.

In order to exclude a surface contamination effect, the specimen was extremely carefully ground again and repolished and then imaged immediately after preparation. The pyramidal structures again could be observed, but were smaller in size and the effect was less expressed (not shown). Therefore, the obvious question occurred, if the formation of the protruding pyramidal structures and their increase in size, in short “their growth,” is really a time-related reaction. In order to study this more carefully, exposures in ambient air (laboratory air with a relative moisture of 27%) at room temperature were carried out to study a possible time

dependence. To achieve this, a certain region was marked on the specimen. The sample was investigated immediately after polishing (0 days). Then, the sample was kept in laboratory air at room temperature for 9 days and for 23 days (Figure 9).

Few very tiny pyramids were already observable immediately after the polishing process. The pyramidal structures clearly increased in size and number over the investigated time period. After 8 months, the sample was checked again and still some development had occurred in the meantime (Figure 10). The amount and size of the pyramidal structures had still increased, cracks have occurred with time, or cracks widened.

To further investigate the nature of the pyramidal structures on the surface of the sample after aging, the sample was selected for transmission electron microscopy (TEM) analysis (Figure 11). TEM imaging of a region with the aging-related surface features shows subsurface cracking (Figure 11b,c), along with planar defects in surface grains (Figure 11c). Selected area diffraction (SAD) and high-resolution scanning transmission electron microscopy (HRSTEM) imaging of the surface grains correlated to the pyramidal structures confirms the presence of a twinned monoclinic phase (Figure 11d,e). By contrast, grains below the surface maintain a tetragonal structure (Figure 11f). EDS mapping of the monoclinic crystal shows Y-depletion in the surface grain which had transformed (Figure 11g).

Low-temperature phase transformations from tetragonal to monoclinic structures have been reported in the literature for YSZ [12, 13], typically believed to be accelerated by the presence of water and slightly elevated temperatures (100–300°C) [8]. Competing hypotheses of the cause of the phase transformation have been postulated previously, with work suggesting that

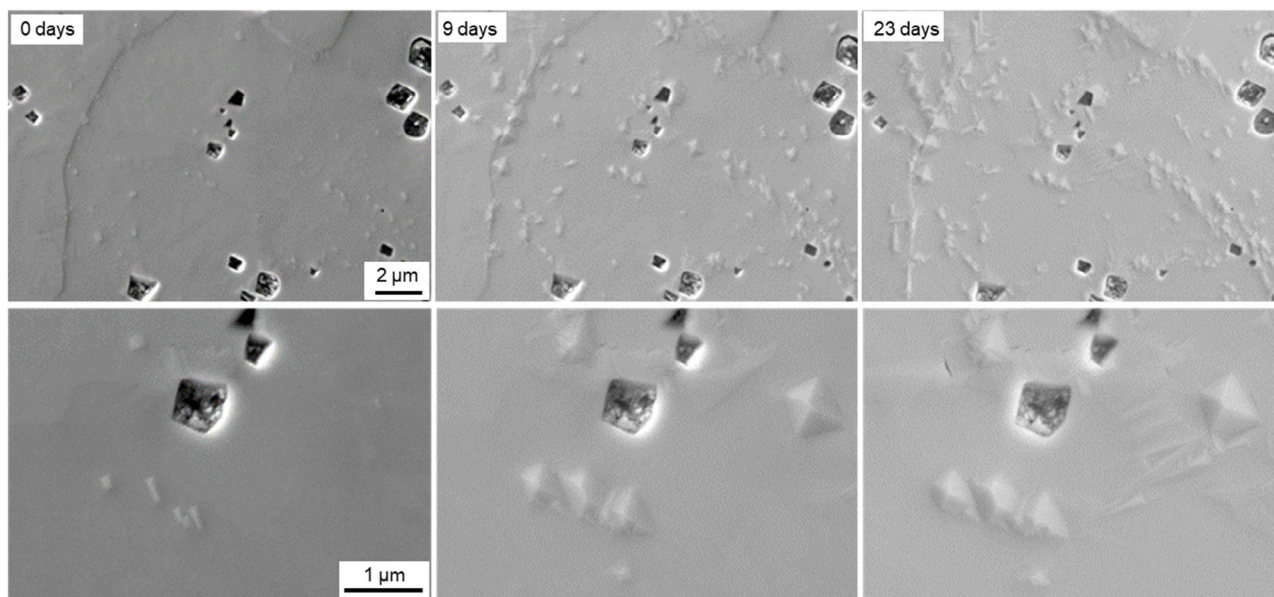


FIGURE 9 | SE images of YSZ after burner rig test at 1554°C in air until failure after 0 days, 9 days, and 23 days exposure in laboratory air at room temperature. SE = Secondary electron; YSZ = yttria-stabilized zirconia.

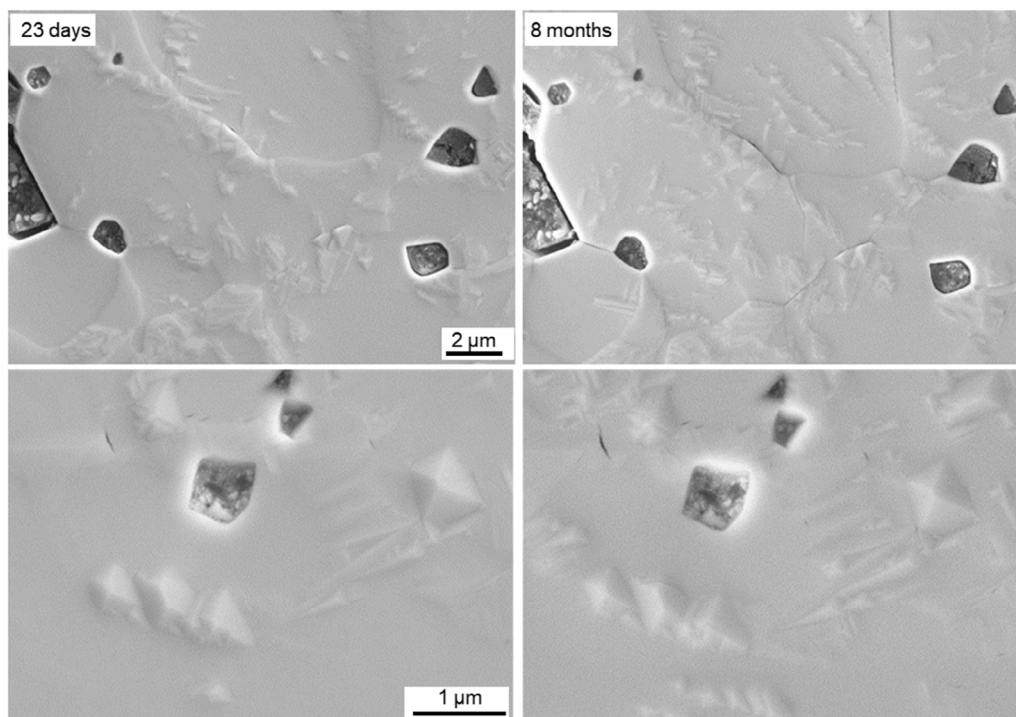


FIGURE 10 | SE images of YSZ after burner rig test at 1554°C in air until failure after 23 days and 8 months exposure in laboratory air at room temperature. SE = Secondary electron; YSZ = yttria-stabilized zirconia.

Y-loss occurs through hydroxide formation [14, 15], and others indicating that internal stresses play a main role [16]. The current work provides evidence that Y-loss plays a large role, as Y-depletion is clearly observed at the surface in grains which have transformed.

Furthermore, the results indicate that TBCs, which have been cycled at high temperatures above 1300°C and do not show a phase transformation due to fast cooling, might form the monoclinic phase during storing at room temperature. Detailed analysis of the kinetics and the impact of water vapor will follow.

3 | Conclusions and Outlook

A 5-YSZ TBC has been cycled in a gradient test rig up to surface temperatures of 1550°C for 1933 cycles given a time at temperature of about 160 h. The high-temperature treatment led to a strong grain growth and densification of the hottest parts of the coating. In polished cross section, pyramidal features could be detected. After repolishing, these features grow again, the amount of features increases with time. SEM-EBSD measurements could partially identify monoclinic phases in the top region of the TBC coating. A detailed analysis underneath the

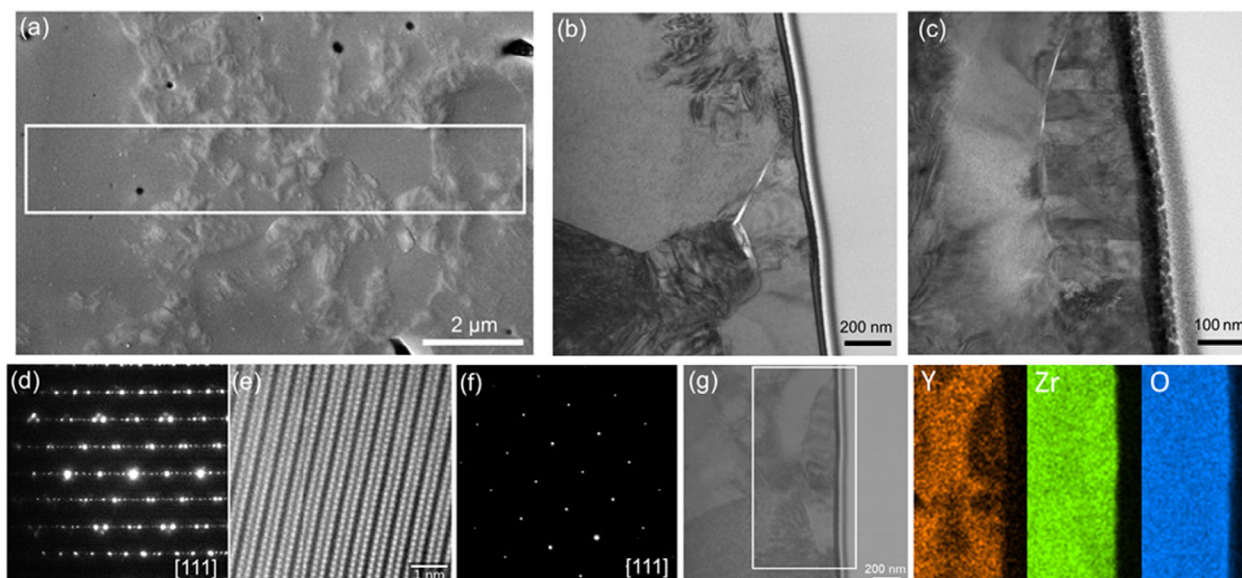


FIGURE 11 | TEM analysis of surface features after aging of a polished cycled YSZ specimen. (a) SEM image with an overlay showing where the TEM sample was taken from. (b,c) Bright-field TEM imaging shows subsurface cracking and planar defects in the regions near the surface. (d) SAD from the surface grain in (c) shows a pattern likely resulting from a twinned monoclinic structure, which is supported by high-resolution STEM high-angle annular dark-field imaging in a near-surface grain (e). A diffraction pattern from an internal grain (f) shows a tetragonal structure. (g) EDS mapping shows a reduced Y signal in the surface grains which maintain the monoclinic structure. TEM = Transmission electron microscopy; YSZ = yttria-stabilized zirconia; SEM = scanning electron microscopy; STEM = scanning transmission electron microscopy; EDS = energy-dispersive spectrometer; SAD = selected area diffraction.

surface was done by TEM. Crystals at the surface with a monoclinic phase and a reduced yttrium content could be identified.

Still, some questions and some unclarities are prevailing, so that further investigations are desirable, but which would go beyond the scope of the present study. The authors believe that this effect should be studied more carefully in the next future, e.g., with X-ray diffraction (XRD). With XRD and subsequent Rietveld refinement, the amount of the cubic and monoclinic phase could be determined. By using on top of that grazing incidence diffraction, information which is to some extent depth sensitive could be obtained and may be correlated to the present study. Also, the prevailing humidity might play a role. This could be tested in future experiments in dry air, humid air, and inert atmosphere. Since cracks appear close to the pyramidal structures, mechanical testing like microhardness and nanoindentation could be helpful to elucidate the impact on TBC durability in a future study. Moreover, at this moment it is unclear if the pyramid formation only takes place at the surface and whether it shortens lifetime or leads in any way to TBC disintegrality. However, our findings indicate that the phase transformation mainly takes place at the surface and not in the bulk of the samples. So, the impact of the transformation might not be as detrimental as the structural integrity of the sample is largely maintained.

In addition to this experimental study, also simulation work using phase field models is ongoing to get further insight in this degradation mechanism and to develop a predictive tool for this kind of phase transformation.

4 | Materials and Methods

4.1 | Sample Production

The disk-shaped specimen (radius 1.5 mm) consisted of a 3 mm thick IN738 substrate, a 0.15 mm NiCoCrAlY bond coat, and a

0.6 mm thick ceramic YSZ topcoat. Before the substrate was coated, it was grit blasted with an F36 corundum abrasive to roughen the surface and therewith improve the adhesion. The substrate was subsequently cleaned with compressed air and in an ultrasonic bath with ethanol before the bond coat was applied. The same procedure was carried out, before coating of the ceramic topcoat.

The NiCoCrAlY bond coat (Oerlikon Metco, Amdry 386) was applied via vacuum plasma spraying in an Oerlikon Metco facility using a F4 torch. The gun was operated at a power of 50 kW and a chamber pressure of 50 mbar using a volumetric gas flow of 50 slpm (standard liter per minute) argon and 9 slpm hydrogen as process gas at a stand-off distance of 275 mm. After bond coat deposition, a diffusion heat treatment was performed in a vacuum furnace (1st step 1120°C, 2h, 2nd step 788°C for 8h). An agglomerated and sintered YSZ powder (H.C. Starck Amperit 827.006, $d_{10} = 54 \mu\text{m}$, $d_{50} = 80 \mu\text{m}$, and $d_{90} = 112 \mu\text{m}$, 7.8 Mol-% $\text{YO}_{1.5}$ -stabilized ZrO_2) was used for the topcoat. The 600 μm topcoat was applied by APS in a Multicoat facility by Oerlikon Metco, Wohlen, Switzerland, with a three-cathode TriplexPro210 gun. The gun was operated with a power of 48 kW with 46 slpm argon and 4 slpm helium at a stand-off distance of 150 mm.

4.2 | Sample Life Time Testing

The lifetime of the disk-shaped specimen was tested in a burner rig test. The details of the burner rig are extensively described in Traeger et al. [17]. So here only a short description is given. The sample is heated with a natural gas/oxygen burner and cooled from the back by compressed air to adjust a gradient across the sample. The dwell time at high temperature is 5 min, the surface is cooled by about 10 K/s by reducing the gas supply of the burner and adjusting simultaneously the cooling air. After

reaching a temperature below 100°C, the temperature is held constant, the total cooling time lasts 5 min. During cyclic testing, the following averaged conditions were applied: $T_{\text{surface}} \approx 1540^\circ\text{C}$, $T_{\text{substrate}} \approx 1043^\circ\text{C}$, $T_{\text{bond coat (calculated)}} \approx 1088^\circ\text{C}$, heating rate $\approx 25\text{K/s}$, low cooling rate $\approx 10\text{K/s}$. It took 1933 cycles to failure.

4.3 | Sample Microstructure

In order to determine the microstructure and the phase distribution of the specimen, a metallographic cross section was produced. First, the sample was completely embedded in epoxy and subsequently cut with a diamond blade saw (Accutom, Struers, Germany). A grinding process, starting with 400 grid sand paper, in steps up to 1200 grid, followed. After this, the sample was polished with a 9, 6, 3, and 1 μm diamond suspension. The last and final polishing step was carried out with a colloidal SiO_2 suspension.

For the SEM study, a field emission gun SEM, a GeminiSEM 450, by Zeiss, Oberkochen, Germany, was utilized. It was equipped with an EDS, namely an ULTIM MAX 170 detector, made by Oxford Instruments, with the software AZtec. For the EBSD study, a C-Nano device, also from Oxford Instruments, was employed. The images taken with the backscatter detector are connotated as BSE images; images taken with secondary electron detector are called SE images.

The sample for TEM analysis was made utilizing an FEI Helios NanoLab 460F1 FIB-SEM, with the liftout location chosen to correlate with surface features. TEM (including bright-field imaging and SAD) was done using an FEI Tecnai G2 F20. STEM, high-angle annular dark-field imaging, and EDS mapping were done utilizing a Hitachi HF5000 S/TEM. HRSTEM imaging was done using a JEOL JEM ARM200F NEOARM. HRSTEM image collection was done through a series of 15 consecutive images, followed by a rigid registration procedure and application of a nonlinear filter developed for denoising of high-resolution S/TEM micrographs [18].

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The detailed information on the SEM/TEM results can be provided by the authors upon request.

References

1. R. Vaßen, M. O. Jarligo, T. Steinke, D. E. Mack, and D. Stöver, "Overview on Advanced Thermal Barrier Coatings," *Surface and Coatings Technology* 205 (2010): 938–942.
2. G. Mauer and R. Vaßen, "Technology Vision: Current Developments and Challenges in Thermal Barrier Coatings," *Surface and Coatings Technology* 27 (2011): 477–479.
3. A. Kulkarni, A. Vaidya, A. Goland, S. Sampath, and H. Herman, "Processing Effects on Porosity-Property Correlations in Plasma Sprayed Yttria-Stabilized Zirconia Coatings," *Materials Science and Engineering: A* 359 (2003): 100–111.
4. I. O. Golosnoy, A. Cipitria, and T. W. Clyne, "Heat Transfer Through Plasma-Sprayed Thermal Barrier Coatings in Gas Turbines: A Review of Recent Work," *Journal of Thermal Spray Technology* 18 (2009): 809–821.
5. E. Bakan and R. Vaßen, "Ceramic Top Coats of Plasma-Sprayed Thermal Barrier Coatings: Materials, Processes, and Properties," *Journal of Thermal Spray Technology* 26, no. 6 (2017): 992–1010.
6. J. A. Krogstad, S. Krämer, D. M. Lipkin, et al., "Phase Stability of t' -Zirconia-Based Thermal Barrier Coatings: Mechanistic Insights," *Journal of the American Ceramic Society* 94 (2011): S168–S177, <https://doi.org/10.1111/j.1551-2916.2011.04531.x>.
7. J. R. VanValzah and H. E. Eaton, "Cooling Rate Effects on the Tetragonal to Monoclinic Phase Transformation in Aged Plasma-Sprayed Yttria Partially Stabilized Zirconia," *Surface and Coatings Technology* 46, no. 3 (1991): 289–300.
8. V. Lughi and D. R. Clarke, "High Temperature Aging of YSZ Coatings and Subsequent Transformation at Low Temperature," *Surface and Coatings Technology* 200, no. 5 (2005): 1287–1291, <https://doi.org/10.1016/j.surfcoat.2005.07.089>.
9. R. Vassen, D. E. Mack, M. Tandler, Y. J. Sohn, D. Sebold, and O. Guillon, "Unique Performance of Thermal Barrier Coatings Made of Yttria-Stabilized Zirconia at Extreme Temperatures ($>1500^\circ\text{C}$)," *Journal of the American Ceramic Society* 104, no. 1 (2021): 463–471, <https://doi.org/10.1111/jace.17452>.
10. S. Q. Tao, J. S. Yang, W. Li, et al., "Thermal Stability of Plasma-Sprayed Thick Thermal Barrier Coatings Using Triplex ProTM-200 Torch," *Coatings* 10 (2020): 894.
11. G. A. Gogotsi, S. N. Dub, E. E. Lomonova, and B. I. Ozersky, "Vickers and Knoop Indentation Behaviour of Cubic and Partially Stabilized Zirconia Crystals," *Journal of the European Ceramic Society* 15, no. 5 (1995): 405–413.
12. J. Chevalier, B. Cales, and J. M. Drouin, "Low-Temperature Aging of Y-TZP Ceramics," *Journal of the American Ceramic Society* 82 (1999): 2150–2154, <https://doi.org/10.1111/j.1151-2916.1999.tb02055.x>.
13. K. Kobayashi, H. Kuwajima, and T. Masaki, "Phase Change and Mechanical Properties of $\text{ZrO}_2\text{-Y}_2\text{O}_3$ Solid Electrolyte after Ageing," *Solid State Ionics* 3–4 (1981): 489–493, [https://doi.org/10.1016/0167-2738\(81\)90138-7](https://doi.org/10.1016/0167-2738(81)90138-7).
14. F. F. Lange, G. L. Dunlop, and B. I. Davis, "Degradation During Aging of Transformation-Toughened $\text{ZrO}_2\text{-Y}_2\text{O}_3$ Materials at 250°C ," *Journal of the American Ceramic Society* 69 (1986): 237–240, <https://doi.org/10.1111/j.1151-2916.1986.tb07415.x>.
15. V. Lughi and V. Sergo, "Low Temperature Degradation -Aging- of Zirconia: A Critical Review of the Relevant Aspects in Dentistry," *Dental Materials* 26 (2010): 807–820, <https://doi.org/10.1016/j.dental.2010.04.006>.
16. D. Kim, "Phase Transformations of Y_2O_3 and Nb_2O_5 Doped Tetragonal Zirconia during Low Temperature Aging in Air," *Solid State Ionics* 80 (1995): 67–73, [https://doi.org/10.1016/0167-2738\(95\)00115-M](https://doi.org/10.1016/0167-2738(95)00115-M).

17. F. Traeger, R. Vaßen, K. H. Rauwald, and D. Stöver, "Thermal Cycling Setup for Testing Thermal Barrier Coatings," *Advanced Engineering Materials* 5 (2003): 429–432, <https://doi.org/10.1002/adem.200300337>.
18. H. Du, "A Nonlinear Filtering Algorithm for Denoising HR(S)TEM Micrographs," *Ultramicroscopy* 151 (2015): 62–67, <https://doi.org/10.1016/j.ultramic.2014.11.012>.