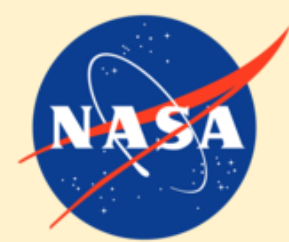




Preliminary Coating Development for Solar Thermal Propulsion (STP)

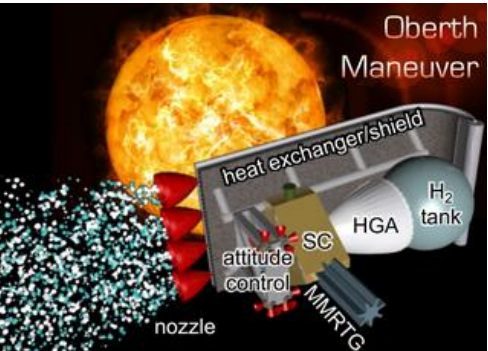


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I. Introduction

Solar Thermal Propulsion (STP) utilizes the sun's thermal energy to create thrust, enabling rapid transit to interstellar medium via the Oberth Maneuver. For this, the system would fly very close to the sun, so an optical, "white" coating on a graphite substance is required to regulate the system's temperature. However, standard heat shield coatings degrade over the STP heating profile of 2500 °K over multiple hours. Thus, an optical coating should be designed with the ability to control reflectance and microstructural evolution during operation.



Graphic depiction of Combined Heat Shield and Solar Thermal Propulsion System for an Oberth Maneuver

[1]

As a pathfinder for this, the viability of ceramic coatings for the application of STP was tested through:

- I. Creating and Refining the Coating Process
- II. Tube Furnace Firings
- III. Analysis
 - I. SEM
 - II. Spectroscopy

II. Coating Selection

The following coatings were selected because they are refractory and white in color - which increases solar reflectance, were commercially available, and a multitude of coatings will allow us to understand the difference in porosity and microstructure. High solar reflectance is optimal to reflect as much energy from the sun as possible to prevent overheating, allowing us to get close enough to the sun to perform an Oberth Maneuver.

YAG (Yttria Aluminate)	YSZ (Yttria-Stabilized Zirconia)	Y-CZ (Yttria Calcium Zirconate)
• $3Y_2O_3-5Al_2O_3$ • Single, crystal phase • 57% wt. Yttria • Max use temperature: 1700 °C	• ZrO_2 stabilized with 7.5 mol% Y_2O_3 • Single, cubic phase • Max use temperature: 2000 °C	• $Y_2O_3-CaZrO_3$ • Two phased • 60 mol% Yttria • 40 mol% Calcium Zirconate • Max use temperature: 2000 °C

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III. Methodology

The samples were prepared by painting the alumina substrate with the three different coatings. YAG and YSZ were then dried in an 80 °C drying oven, while Y-CZ was dried in a fume hood overnight to prevent cracking. Although the application requires a graphite substrate, alumina plates were readily available and suffice for preliminary testing.

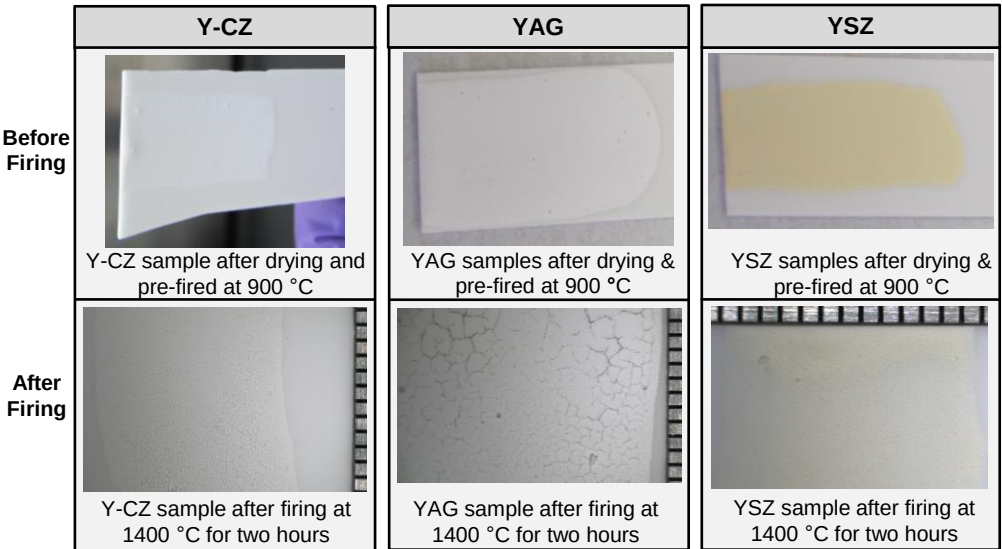
To further drive water out of the Y-CZ samples, they were fired in a furnace at 100 °C for 15.5 hours. All samples were then pre-fired at 900 °C for two hours to allow for outgassing before firing at higher temperatures.

The samples were then fired in a tube furnace at our incremental target temperatures of 1200 °C, 1300 °C, and 1400 °C for two hours.

Afterwards, samples were cross-sectioned and analyzed under a scanning electron microscope (SEM), while others were used to collect spectroscopy data with an integrating sphere. For this, we focused only on the samples fired at 1400 °C, because they showed major changes in microstructure and porosity, whereas the 1200 °C and 1300 °C samples did not.

IV. Optical Analysis

A. Optical Images Before & After Firing at 1400 °C



After firing, many micro-cracks were visible in the Y-CZ sample, which tended to increase with a rise in temperature as observed with the 1200 °C and 1300 °C samples.

YAG also cracked, especially the parts that applied thicker (the edges). Similarly, an increase in temperature led to an increase in the number and size of cracks throughout the samples fired at incremental temperatures.

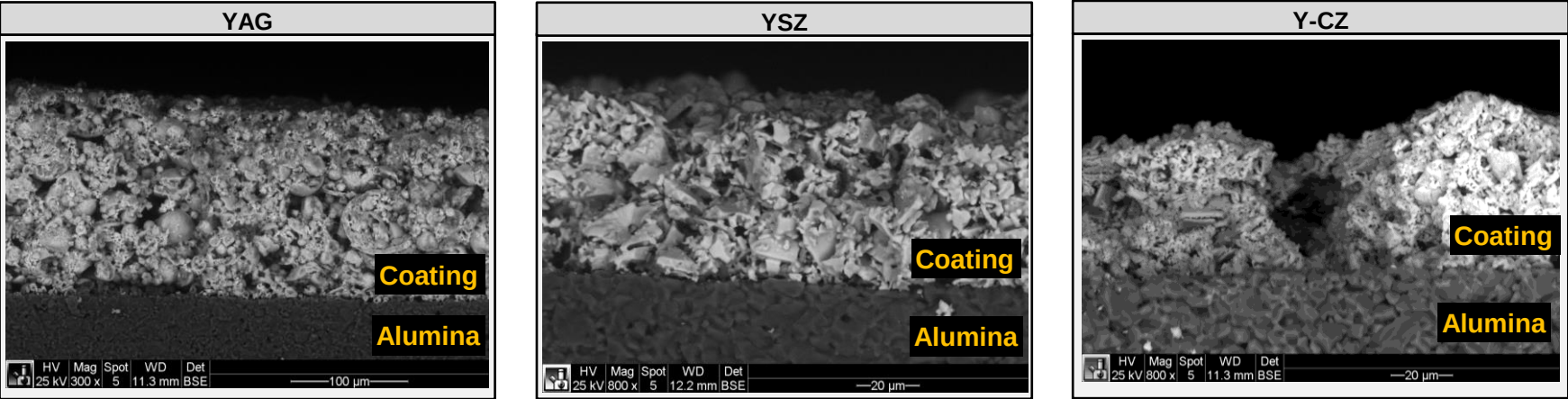
YSZ turned notably lighter and maintained its granular structure, showing no signs of cracking.

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V. SEM Analysis

B. SEM Cross-Sectional Images after Firing at 1400 °C



Sintering effects are unclear because the sintered microstructure may be like the regular microstructure with the spherical features.

In the YSZ sample, the small particles sintered and coarsened whereas the larger particles did not, suggesting that it should be fired at a higher temperature.

The Y-CZ sample sintered significantly at this temperature, as evident by the fusion of the smaller and larger particles.

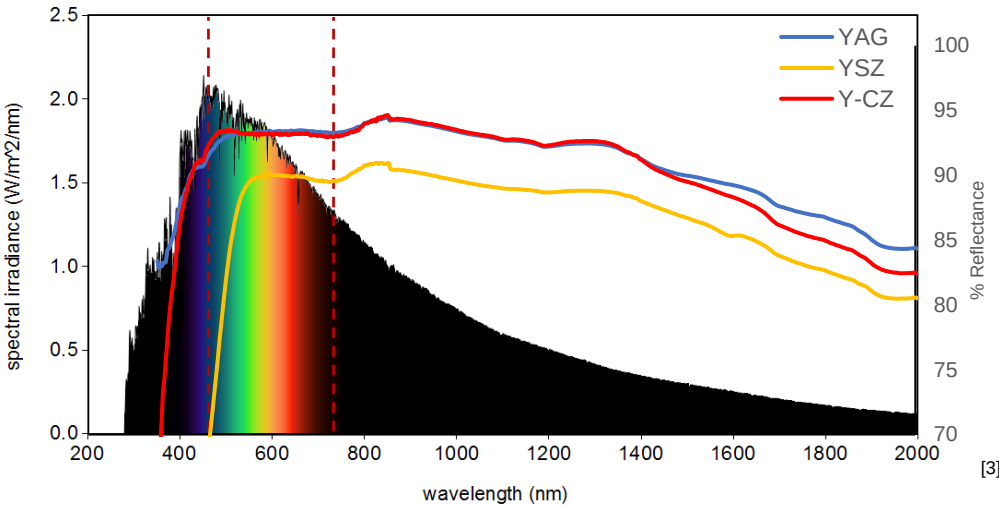
Placing this in perspective of STP, sintering occurs far earlier than we would want. Some effects of this can be seen in the spectroscopy data.

VI. Spectroscopy Analysis

C. Spectroscopy of YAG & YSZ Samples after 1400 °C Fire Overlaid on the Sun's Energy Spectrum

As figure C. indicates, the YAG and Y-CZ samples are roughly 4% more reflective than the YSZ sample, which is to be expected based on the coatings' appearances.

Focusing on the ranges of the sun's energy, YAG and Y-CZ can reflect more energy in this range, thus increasing solar reflectance, proving them to be optical candidates for STP as opposed to YSZ. On top of that, YAG reflects far more energy in the UV range than YSZ and slightly more than Y-CZ. However, the issues of cracking need to be resolved, as the coatings needs to withstand far higher temperatures than 1400°C.



[3]

VII. Conclusion

From this preliminary testing of several coatings, YAG and Y-CZ are better suited for the application of STP than YSZ due to their higher reflectance in the energy ranges of the sun (Fig. C). However, they do crack at temperatures that are low for the application. There are two sources of cracking: shrinkage, and thermal mismatch (CTE). To mitigate cracking, further research is listed in the next steps.

VIII. Next Steps

Different substrate:

- Porous carbon-based substrate to increase fidelity and decrease cracking

Different application methods:

- Use thermal spraying to eliminate shrinkage of coating and therefore cracking
- Increase coating layers to achieve optical thickness

Acknowledgements

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References

- [1] www.nasa.gov/directorates/spacetech/niac/2022/Combined_Heat_Shield_and_Solar_Thermal_Propulsion_System/
- [2] Provided in respective data sheet by ZYP Coatings
- [3] Christopher S. Baird, American Society for Testing and Materials Terrestrial Reference