ULTRA-HIGH TEMPERATURE THERMAL BARRIER COATINGS

DOE Phase II STTR Project

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1. Summary

A thermal barrier coating (TBC) with a 1500°C temperature capability would be a major gas turbine materials "breakthrough." This represents more than a 200°C temperature advantage compared to the current air plasma spray (APS) yttria-stabilized zirconia (YSZ) and can be used by the gas turbine industry to significantly increase turbine efficiency and reduce fuel consumption. In a current DOE Phase II STTR, HiFunda and UConn have successfully demonstrated that yttrium aluminum garnet (YAG) deposited by the Solution Precursor Plasma Spray (SPPS) process has a 1500°C temperature capability along with excellent durability. In the Phase II program, the 1500°C temperature capability was demonstrated based on sintering, phase stability and CMAS resistance tests. The excellent durability of SPPS YAG TBCs was demonstrated using thermal cycling and particulate erosion tests. The strain-tolerant microstructure of the SPPS YAG TBCs provides the excellent thermal cycling durability. The high temperature thermal conductivity is equal to or somewhat lower than that of baseline air plasma sprayed YSZ TBCs. Based on these promising results, our five industrial partners are carrying out in-house testing on SPPS YAG TBCs and evaluating the SPPS process in production facilities.

2. The Innovation

The HiFunda/UConn approach is to use a yttrium aluminum garnet (YAG, $Y_3Al_5O_{12}$) material as a TBC, which as a bulk material has proven thermal stability and excellent high-temperature mechanical properties. YAG is an excellent choice due to its robust high temperature properties and phase stability up to its melting point (1970°C). YAG TBCs will have much higher use temperature, low thermal conductivity and density, and improved durability compared to APS YSZ. Some of the improved properties for YAG TBCs will be enabled by use of the SPPS process that provides a highly strain-tolerant microstructure.

However, despite these excellent properties, YAG TBCs had not been successfully implemented to date because they exhibit inadequate durability greater thermal expansion mismatch strains compared to 7YSZ. The hypothesis at the start of the Phase I was that a strain-tolerant microstructure such as could be produced through a solution precursor plasma spray (SPPS) process could produce durable higher temperature TBCs. The Phase I and II work demonstrated the feasibility of that concept and of SPPS YAG TBCs. Figure 1 shows a schematic of the SPPS process. A liquid chemical precursor, containing the desired cations, is atomized into the plasma jet. The injected solution is first evaporated, the resulting salts are pyrolyzed and then they are melted and deposited as micron-sized splats. These splats are much finer, typically less than 5 microns, compared to 125 microns for the state of the art air plasma spray (APS) coatings. The fine splat structure imparts many favorable properties such as significantly higher in-plane fracture toughness and negligible residual stress in SPPS coatings. Full thickness SPPS YAG TBCs and a YSZ interlayer were fabricated with desirable microstructures on superalloy specimens provided by major engine manufacturers (example shown in Figure 2).

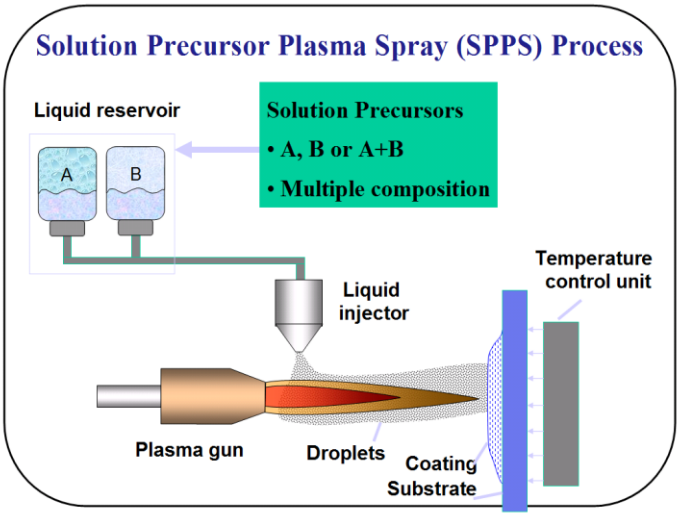
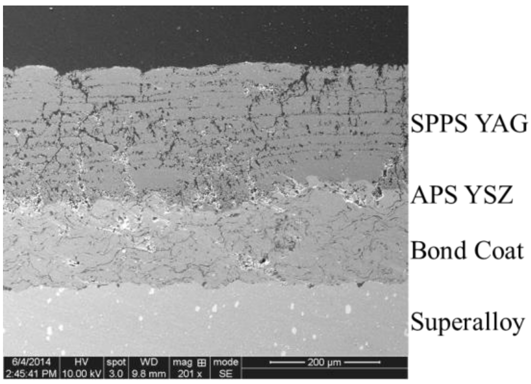


Figure 1. Schematic of SPPS process



- **Vickers Hardness: 200-400**
- **Porosity: 15-20%**

Figure 2 Strain Tolerant YAG TBCs fabricated by the SPPS process

3. Key Accomplishments

The major goals and objectives for the Phase II have all either been accomplished or are on track to being accomplished. One of the major objectives of Phase II was to meet or exceed the performance of state of the art APS YSZ TBCs from the stand point of a number of engine critical properties, that can raise the confidence on engine manufacturers in adopting the new SPPS YAG technology. A list of these engine critical properties and how SPPS YAG TBCs performed head to head against state of the art APS YSZ TBCs especially at higher temperatures in the range of 1300-1500^{o}C is provided in Table I and Figures 2-7 below.

Engine Critical Property	**Performance of SPPS YAG TBCs against baseline state of the art APS YSZ TBCs**
Phase Stability (limits upper use temperature)	***Superior:*** YSZ undergoes a phase transformation above 1300^{o}C. YAG shoes no phase changes until its melting point – Figure 3 shows the phase stability of YAG to 1600^{o}C. (Figure 3)
Sintering Resistance (higher sintering resistance retains performance and improves lifetime of TBCs)	***Superior:*** SPPS YAG TBCs retain their microstructure and density after high temperature exposures much better than APS YSZ. (Figure 4)
Thermal Cycling Performance (Measure of durability during start up and shut down cycles)	***Similar:*** Despite the higher thermal expansion mismatch, SPPS YAG TBCs performed at least as good as, and in some cases slightly better than APS YSZ TBCs. (Figure 5).
Erosion Resistance (Measure of durability to particle impingement when carried by high velocity gas flow)	***Superior:*** Standard erosion resistance testing done at The Pennsylvania State University shows SPPS YAG TBCs having lower erosion rates than APS YSZ under both 30^{o} and 90^{o} impingement angles (Figure 6)
Thermal Conductivity (Lower thermal conductivity allows higher operating temperatures with thinner coatings, reducing cost and increasing durability)	***Superior:*** Operating temperature thermal conductivity of SPPS YAG measured to be lower than that of APS YSZ (Figure 7)
Chemical Stability and Durability with exposure to calcium magnesium aluminosilicate – CMAS	***Superior:*** Thermal cycling with CMAS suspension sprayed on the surface showed significantly improved life for SPPS YAG TBCs compared with APS YSZ. (Figure 8).

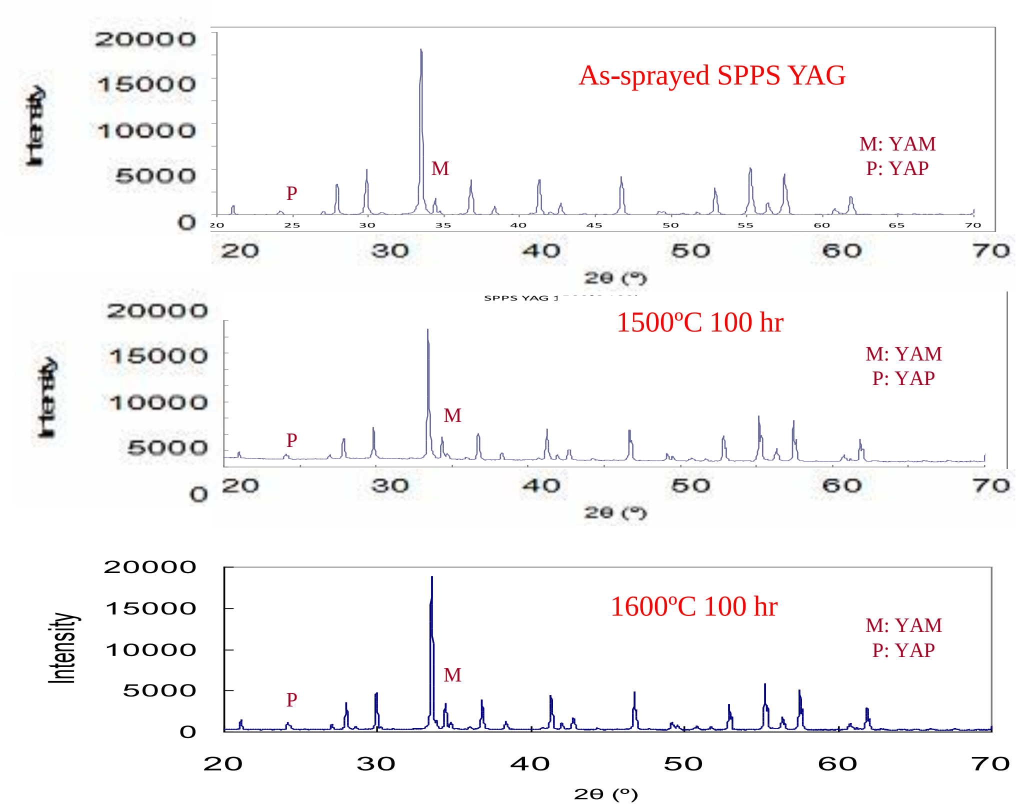
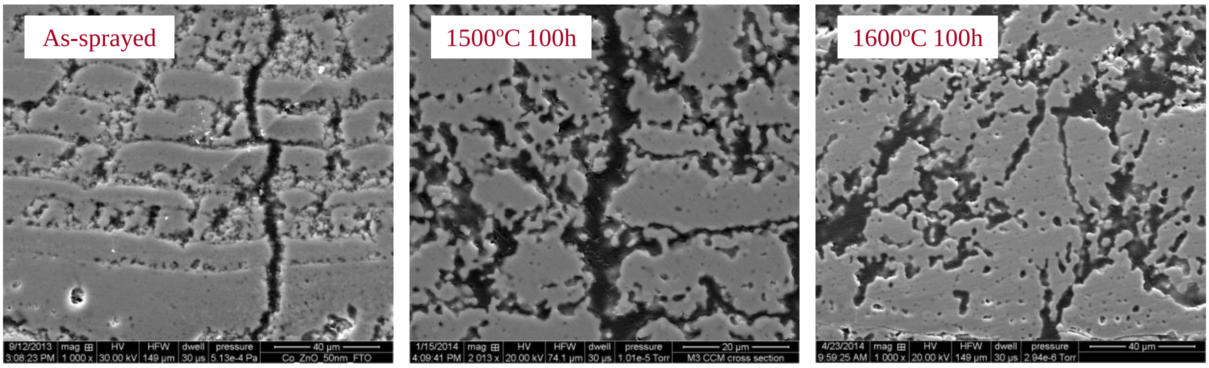


Figure 3 SPPS YAG TBCs have phase stability to at least 1600ºC



HV = 380±185 **HV = 324±122** **HV = 378±139**

Figure 4 SPPS YAG TBCs have sintering resistance to at least 1600ºC

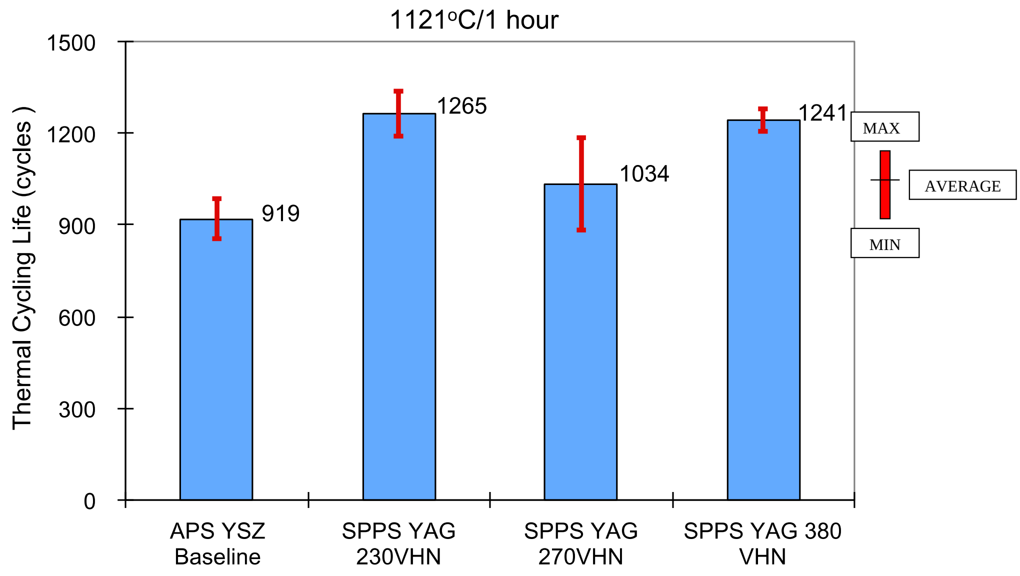


Figure 5 SPPS YAG TBCs outperformed state of the art APS YSZ TBCs in standard thermal cycling tests

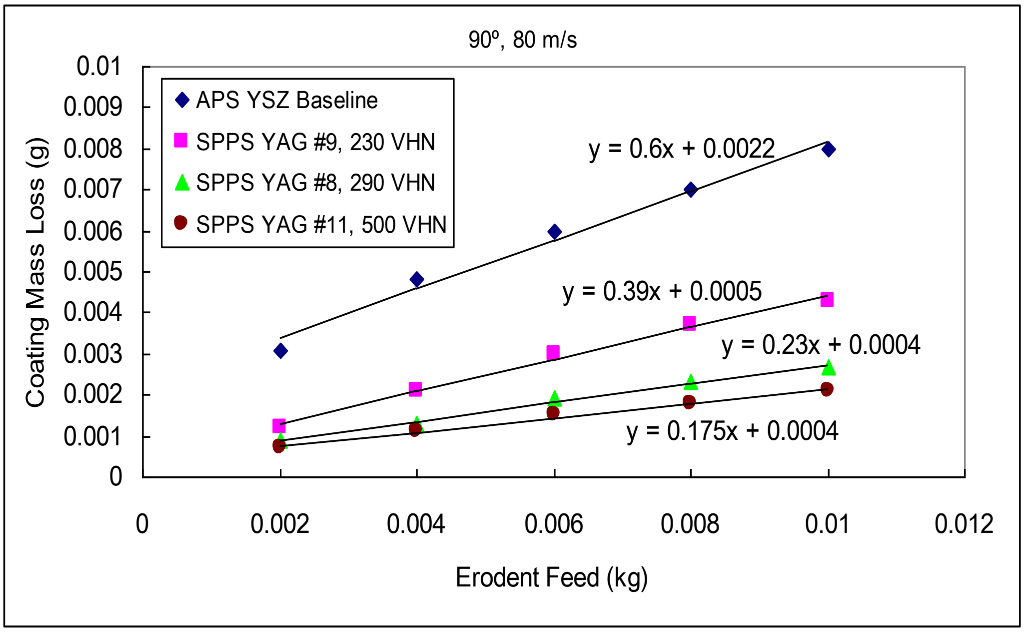
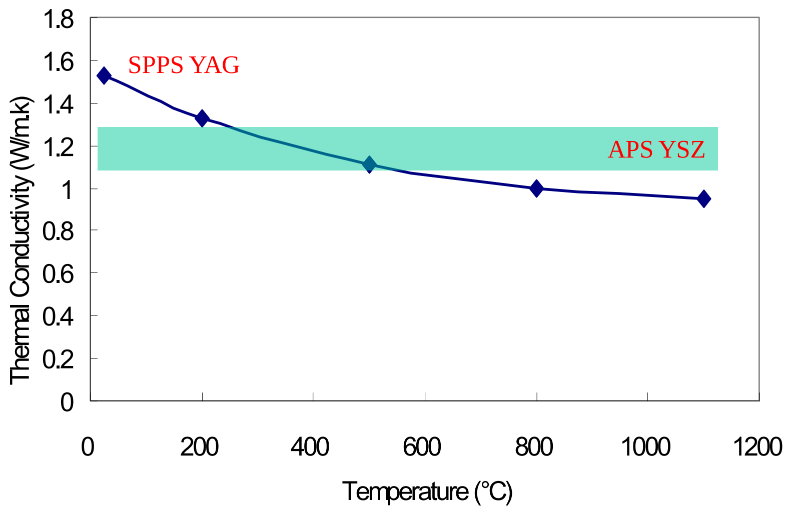


Figure 6 SPPS YAG TBCs outperformed state of the art APS YSZ TBCs in erosion testing conducted at Penn State.



- **Measured by Netzsch Instruments Using Laser Flash**

Figure 7 SPPS YAG TBCs have lower thermal conductivity than APS YSZ TBCs at operating temperatures.

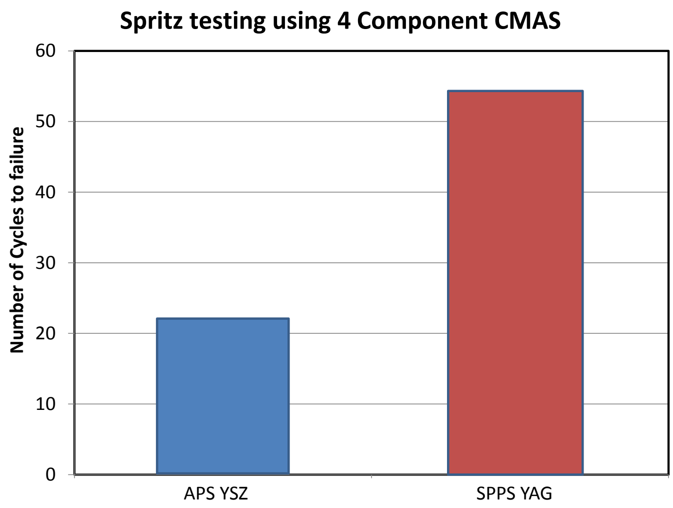


Figure 8 SPPS YAG TBCs have superior resistance to CMAS than APS YSZ TBCs.

4. Conclusions

SPPS YAG TBCs have been shown to have superior thermal cycling durability, erosion resistance, CMAS Resistance, thermal conductivity and sintering resistance (>200°C) relative to the industry standard APS YSZ. As such, SPPS YAG represents a step change in operating temperature capability that has the potential to significantly enhance the efficiency of gas turbines and the durability of gas turbine components.