Deposition of YSZ Thin Films by Atmospheric Plasma-Assisted Pulsed Laser Ablation

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***Abstract*—Yttria-stabilized zirconia (YSZ) thin films have been deposited on a nickel-based substrate by a laser-assisted plasma coating technique at atmospheric pressure. The substrate is heated by an atmospheric plasma torch to 800 °C to form a thermally grown oxide layer and is increased to 1000 °C during film deposition. The deposited films show columnar structures similar to films deposited in high-vacuum deposition methods. The microstructures of the deposited YSZ films have been examined by focused-ion beam and X-ray photoelectron spectroscopy.**

***Index Terms*—Atmospheric plasma, laser-assisted plasma coating at atmospheric pressure (LAPCAP), thermal barrier coating, yttria-stabilized zirconia (YSZ) film.**

YTTRIA-STABILIZED ZIRCONIA (YSZ) is a suitable thermal barrier coating material for gas turbine engines, combustion chambers, and mechanical systems for its capabilities of increasing system operation temperature and protecting thermal corrosions [1], [2]. In most of these applications, an ideal YSZ film morphology is the uniform columnar structure, and slight porosity is sometimes required in order to compensate the heat expansion of these columns. However, YSZ films prepared by traditional methods such as air plasma spraying, electron beam-physical vapor deposition, and pulsed laser deposition yield either a highly porous lamellar microstructure or a slow deposition rate at high costs [3].

In this paper, laser-assisted plasma coating at atmospheric pressure (LAPCAP) has been investigated as an improved technique to prepare columnar-structured YSZ thin films. A laser is used to ablate YSZ into nanoscale particles, and the atmospheric plasma is used to heat the substrate and entrains these particles to reach the substrate. LAPCAP does not require vacuum systems and heat sources for the target and substrate and may have many other favorable advantages such as high deposition rate and low process cost.

Fig. 1 shows the schematic of the LAPCAP system and the operation image during the deposition process. An atmospheric helium plasma is generated in a plasma torch by a 2.45-GHz microwave generator. The plasma torch consists of three copper hollow cylinders, a tungsten antenna at the center, and a quartz discharge tube that has an inside diameter of 13 mm. A cylindrical YSZ target (3 mol.% Y_2O_3) is placed in the notch at the top of the antenna, and the substrate is placed at $\sim$0.5 mm away from the top of the target in a facing-down position. A mixture of helium (99%) and oxygen (1%) is used to generate a large-volume and high-temperature plasma plume to heat the substrate. The YSZ film deposition is a two-step process: First, the substrate is heated to $\sim$800 °C for 60 min by a helium/oxygen plasma to form a thermally grown oxide (TGO) layer on the surface [4]; second, the substrate temperature is increased up to $\sim$1000 °C by a helium plasma, and a pulsed Nd:YAG laser (532-nm wavelength, 100 Hz, and 120 mJ per pulse) is focused to ablate the target at a $\sim$10 J/cm^2 ablation energy density.

Fig. 2 shows the focused-ion beam images of the YSZ films prepared by LAPCAP for deposition times of 15 s and 2 min, respectively. A 50-μm platinum–aluminide bond coat has been deposited on the substrate in order to increase adhesion. The columnar structure can be clearly seen in both films. However, the column size, which is closely related to the film porosity, is increased from $\sim$200 nm for a thinner film [see Fig. 2(a)] to $\sim$1 μm as the film thickness increases [see Fig. 2(b)]. In addition, both films in Fig. 2, the initial film grown on the TGO layer, show that the column size increases when the film gets thicker. These results indicate that the TGO layer, which bonds the YSZ film and the substrate, is a key for the morphology of the films. The film porosity can be modified by the substrate temperature, as we have shown in our previous work [5].

The YSZ films prepared were analyzed by X-ray photoelectron spectroscopy (XPS), as shown in Fig. 3. Three XPS traces from (a) the YSZ film, (b) surface after 30-min sputtering, and (c) TGO layer reveal that YSZ films have various peaks of Y and Zr and the TGO layer shows more Al and O rather than Zr. It confirms that the film produced by the technique is to be YSZ on TGO. In the previous study, the X-ray diffraction patterns of the YSZ target and the YSZ films prepared by this technique were compared and concluded that the films were fully stabilized in a cubic phase and the primary diffraction peak is on the (111) plane of the YSZ cubic, whereas (111) and (220) diffraction peaks are almost equivalent in the YSZ target [5].

In summary, columnar-structured YSZ thin films have been successfully deposited on the nickel-based substrate by the LAPCAP technique. A high deposition rate of $\sim$1 μm/min is obtained by LAPCAP, and the bonding between the YSZ films and the substrate is solid by the TGO layer. The column sizes of the films are gradually increased as deposition time increases. These results can be also determined by the morphology of the TGO layer.

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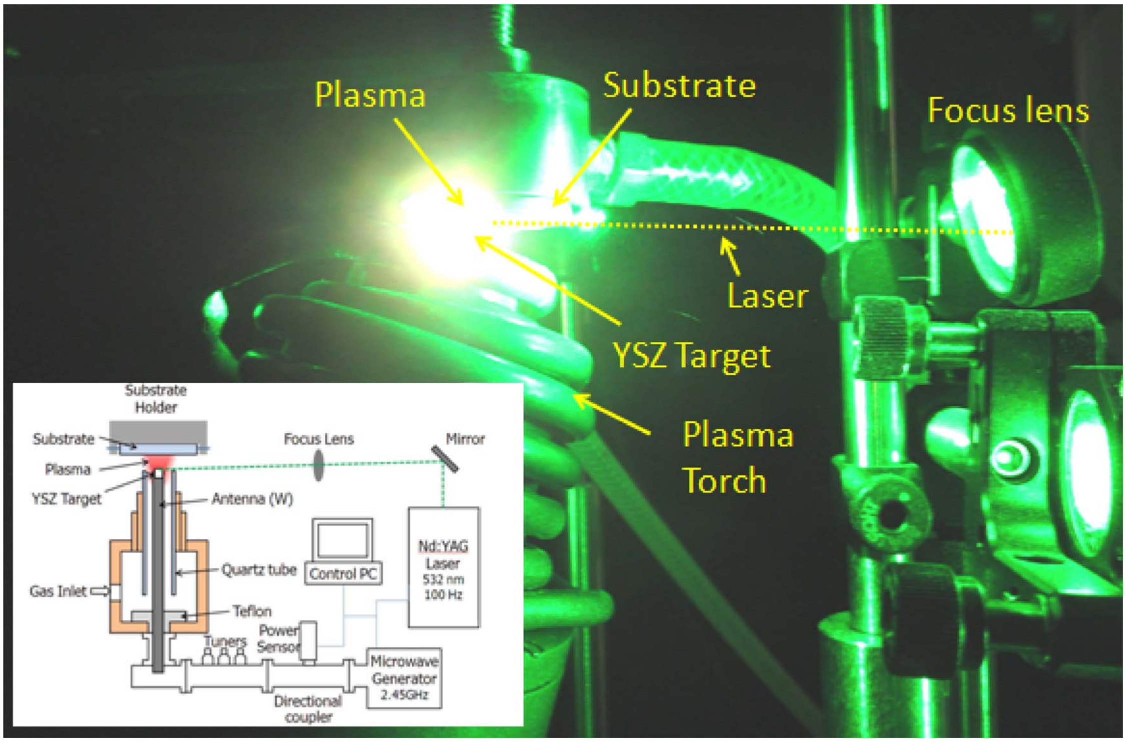

Fig. 1. LAPCAP schematic (inset) and film deposition in operation.

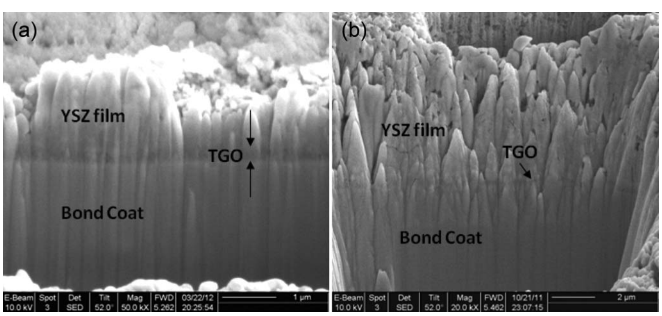

Fig. 2. Microstructure of the LAPCAP YSZ films for deposition times of (a) 15 s and (b) 2 min. The deposition rate is approximately 1 μm/min.

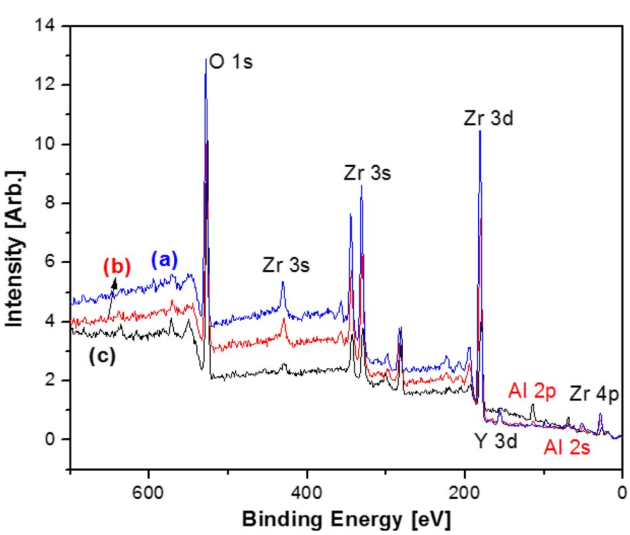

Fig. 3. XPS results for (a) the YSZ film, (b) surface after 30-min sputtering, and (c) TGO layer.

REFERENCES

[1] S. M. Meier and D. K. Gupta, "The evolution of thermal barrier coatings in gas turbine engine applications," *Trans. ASME*, vol. 116, pp. 250–256, Jan. 1994.

[2] S. C. Singhal, *High Temperature Solid Oxide Fuel Cells: Fundamentals, Design and Applications*, K. Kendall, Ed. Amsterdam, The Netherlands: Elsevier, 2003.

[3] C. C. Berndt, P. Michlik, and O. Racek, "The effect of YSZ microstructure on Young's modulus," in *Proc. Int. Thermal Spray Conf.*, Osaka, Japan, 2004, pp. 1110–1118.

[4] A. L. Dragoo and J. J. Diamond, "Transitions in vapor-deposited alumina from 300 ° to 1200 °C," *J. Amer. Ceram. Soc.*, vol. 50, no. 11, pp. 568–574, Nov. 1967.

[5] Z. Ouyang, T. S. Cho, and D. N. Ruzic, "Laser-assisted plasma coating at atmospheric pressure: production of yttria-stabilized zirconia thermal barriers," *J. Phys. D, Appl. Phys.*, vol. 44, no. 26, p. 265 202, Jul. 2011.

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